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FINAL PROJECT REPORT

POWER GENERATION INTEGRATED IN BURNERS FOR INDUSTRIAL/COMMERCIAL PACKAGED BOILERS

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PREPARED BY:

Primary Author(s):
Carlo Castaldini

CMC Engineering
Santa Clara, CA

Contract Number: 500-10-009

Prepared for:

California Energy Commission

Avtar Bining
Contract Manager

Fernando Pina
Office Manager
Energy Systems Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Power Generation Integrated in Burners for Packaged Industrial/Commercial Boilers is the final report for the Power Generation Integrated in Burners for Packaged Industrial / Commercial Boilers project (contract number 500‑03‑037) conducted by CMC-Engineering. The information from this project contributes to Energy Research and Development Environmentally Preferred Advanced Generation Program.

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ABSTRACT

Conventional microturbine-based combined heat and power systems consist principally of a recuperated microturbine coupled with a hot water heat exchanger. Their applications are mostly limited to commercial sites where hot water can be utilized. Overall combined heat and power efficiency is about 70 percent. A simple-cycle microturbine integrated with an industrial packaged boiler where the high quality steam production is the primary method for microturbine waste heat recovery has the potential for over 80 percent combined heat and power efficiency while providing added economic and operational benefits to industrial boiler owners. But they must comply with the California Air Resources Board 2007 distributed generation emission requirements as well as meet local air permit levels.

The purpose of this project was to develop and demonstrate a novel combined heat and power package that integrated a simple-cycle 80 kilowatt electrical microturbine with a gas-fired ultra-low nitrogen oxide burner boiler. The package was designed to: (1) achieve maximum overall electrical and thermal efficiency; (2) meet California Air Resources Board 2007 distributed generation emission requirements; (3) meet local air permit limits for industrial boilers; (4) reduce the carbon footprint; and (5) minimize the cost of small-scale combined heat and power systems to promote the adoption of microturbine-based combined heat and power in industrial and commercial plants.

The combined heat and power technology achieved all its technical objectives and was successfully demonstrated for the first time on an industrial boiler. The microturbine achieved nitrogen oxides significantly below the California Air Resource Board 2007 distributed generation emission limits with about 82.7 percent combined heat and power efficiency. Overall nitrogen oxide emissions from the boiler were reduced by more than 50 percent. Carbon dioxide reduction was 0.17 to 0.27 tons per megawatt hour relative to central power stations, helping to mitigate global climate change impacts.

Keywords: Industrial boilers, commercial boilers, low-NO_x industrial burners, microturbine generators (MTG), combined heat and power (CHP), distributed generation (DG), distributed energy resources (DER)

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EXECUTIVE SUMMARY

Introduction

Package gas-fired industrial and commercial steam boilers require about 20 to 200 horsepower (hp) (15 to 150 kilowatt electrical) to power auxiliary equipment such as combustion air fans, pumps, and controls. The implementation of advanced ultra-low nitrogen oxide (ULN) burners necessary to meet boiler nitrogen oxide (NO_x) emission standards has increased this energy consumption due to requirements for flue gas recirculation (FGR) and increased burner back pressure. The demand for higher FGR rates has resulted in larger capacity combustion air blowers in addition to the higher cost of ULN burners, further adding to the overall capital and operating costs of boiler NO_x compliance in California.

Commercial and industrial steam boilers offered as a packaged design equipped with single burners provide an ideal thermal sink for the waste heat from microturbines used in distributed generation (DG). These combined heat and power (CHP) applications have the potential for overall fuel efficiencies of 80 percent or more. The onsite power generated by the microturbine can readily offset boiler electrical power needs, isolating boiler operation from potential power outages. Furthermore, the more efficient recovery of microturbine waste heat in the boiler compared to conventional microturbine recuperators reduces the investment and maintenance costs of DG/CHP while also reducing or eliminating entirely the requirements for boiler FGR for NO_x compliance. Adding these operational and economic benefits to the conventional CHP savings of voided power purchase could result in an increasingly attractive return on investment (ROI) that could improve acceptance of small-scale DG in industrial/commercial markets. The energy savings associated with the widespread implementation of these efficient CHP systems could translate to significant reductions in greenhouse gas emissions (GHG), which would contribute to the attainment of California climate change mitigation goals.

Project Purpose

The purpose of this project was to develop a new CHP package that integrated a low-cost simple cycle (unrecuperated) microturbine with a ULN industrial boiler burner that would be compliant with California Air Resource Board (ARB) 2007 DG emission limits. The integrated microturbine-burner assembly was to be configured into a small footprint CHP package with maximum waste heat recovery from the turbine exhaust gas (TEG) and 100 percent heat recovery from all other convective heat losses. The integrated microturbine-ULN burner CHP technology was to be applicable to industrial and commercial firetube and watertube boilers with firing capacities of 5 to 100 million British thermal units per hour (MMBtu/hr) using ULN burners. All sensible and convective waste heat from the microturbine was targeted for recovery in the boiler, which would result in overall system efficiencies exceeding 80 percent, significantly higher than conventional recuperators used in commercial microturbine packages. The compact burner-microturbine integrated design allowed for ease of retrofit to existing boilers as well as for new package boiler installations.

The project had the following technical objectives:

- Overall CHP efficiency of greater than 80 percent (or boiler equivalent).

- A DG installed cost of $700/kilowatt electrical (kWe).
- CHP NO_x and carbon monoxide (CO) emissions in compliance with local air permit rules and ARB 2007 DG emission requirements.
- A fully integrated microturbine-ULN burner assembly with maximum waste heat recovery, integrated controls and improved boiler operation.

Project Results

The California Energy Commission (Energy Commission) and Southern California Gas Company (SoCalGas) co-sponsored the development and demonstration of this novel CHP technology for industrial/commercial packaged boilers. CMC-Engineering along with Coen Company, Lawrence Berkeley National Laboratory (LBNL) and Calnetix Power Solutions (CPS) successfully developed and demonstrated the application of a simple cycle microturbine integrated with a ULN burner into a compact CHP package that could be retrofitted on existing and new single burner industrial and commercial boilers.

The technical effort for the project was segmented into seventeen individual tasks targeting four key development and demonstration phases:

1. A simple cycle 80-kWe microturbine was purchased and modified to adapt a new low NO_x silo combustor capable of meeting the ARB 2007 DG requirements. The new silo combustor was designed, fabricated, and successfully tested under this project as a replacement for the high partial oxidation combustor in the original equipment.
2. A new enclosure for the simple cycle microturbine was designed and fabricated to achieve close integration with the windbox of an industrial packaged boiler to achieve maximum recovery of all sensible and convective waste heat from the microturbine.
3. A Coen industrial burner windbox was modified to permit the channeling of microturbine TEG to assist a Coen QLN™ operation in achieving boiler NO_x emission levels below those permitted by the local air district that had jurisdiction over the demonstration site, with reduced combustion air and no external FGR. Burner and microturbine controls were also integrated to permit ease of operation and incorporate necessary safety interlocks.
4. The completed CHP assembly was successfully retrofitted and demonstrated on an industrial package boiler. The retrofit called for issuance of new air permit emission limits that were incorporated into the technical objectives of the project. Field tests were performed and attainment of all performance and emission objectives was successfully demonstrated.

NO_x emissions from the microturbine were reduced from 18-22 parts per million (ppm) to about three ppm, corrected to 15 percent oxygen (O_2) using a new fully premixed silo combustor. The combustor design utilized pilot assist for safe startup and was capable of operating stably at an equivalence ratio of 0.58 at the full 80 kWe load. Low NOx emissions from the microturbine were important for compliance with permitted boiler emission limits as well as compliance with ARB 2007 emission requirements for DG since microturbine NO_x was additive to the NOx formed by the boiler ULN burner.

The simple cycle microturbine enclosure was designed and fabricated to achieve 100 percent recovery of all sensible and convective waste heat, including recovery of heat losses normally associated with generator cooling and heat accumulation in the microturbine enclosure.

The windbox was modified to allow channeling of TEG into the Coen ULN burner in a way that achieved NO_x compliance with the local air district limit of 15 ppm corrected to three percent O_2 and without the use of FGR. High temperature TEG also provided improved burner stability at partial boiler loads.

The new integrated CHP package was retrofitted and tested on a 30 MMBtu/hr industrial boiler located at the steam plant of Hitachi Global Storage Technology (HGST) in San Jose, CA. The CHP installation successfully demonstrated the following performance:

- CHP efficiency was 82.7 percent.
- NO_x emissions from the microturbine were 0.045 lb/MWhr (electrical and thermal).
- NO_x emissions from the boiler with and without microturbine firing were less than 15 ppm, dry corrected to three percent O_2.
- CO emission from the boiler with boiler only firing was less than 25 ppm, dry corrected to 3 percent O_2.
- CO emissions from the boiler with both boiler and microturbine firing were less than 10 ppm, corrected to three percent O_2, corresponding to 0.045 lb/MWhr (electrical and thermal).
- CO_2 emission reduction was 0.17 to 0.26 tons/MWhr.

The measured emissions satisfied the ARB 2007 DG emissions requirements for NO_x (0.07 lb/MWhr electrical and thermal) and CO (0.10 lb/MWhr electrical and thermal). Compliance with CO emissions required the boiler to be online whenever the microturbine was generating power to reduce CO emissions from the microturbine. Compliance was also achieved with the local air district permit limits for the retrofitted boiler for NO_x (15 ppm, dry corrected to three percent O_2) and CO (50 ppm, dry corrected to three percent O_2).

The researchers drew the following conclusions regarding the ability of this technology to address the potential DG CHP market and improve performance and cost:

- Field tests of a novel integrated CHP assembly retrofitted to an industrial packaged boiler successfully demonstrated that low-cost, low-emissions, simple cycle microturbines can be integrated with conventional ULN burners to provide significant energy savings to industrial users while meeting California DG emission requirements and local air emission limits.
- Integrating a low-cost microturbine with an industrial ULN burner provided significant synergies that resulted in lower boiler emissions, reduced carbon footprint, energy savings, and improved boiler operation.

Industrial and commercial boilers provide a large retrofit market for integrated CHP installations and the researchers believed that this newly developed CHP technology should be further pursued in additional field demonstrations. Additional demonstrations will allow boiler owners and operators to become increasingly familiar with the technology and its economic and operational benefits. Integration of a microturbine with a ULN burner into one commercial package should provide greater acceptance of small-scale DG in industry and commercial steam plants.

Project Benefits

All CHP systems provide important benefits to the electricity ratepayers in California and to the attainment of global climate change mitigation goals. CHP systems make better use of fuels by recovering the prime mover waste heat in the form of steam, hot and chilled water, or warm air. It is this waste heat recovery and utilization that makes power generation with CHP less costly and more competitive with central power stations. Additional benefits of CHP can include reduced demand on grid power and transmission, peak shaving, and a reduced carbon footprint.

Specifically, the CHP technology developed and demonstrated in this project could provide the following benefits to California:

- Targets an important large retrofit CHP market consisting of over 1,300 package industrial boilers.
- Has the capability of increasing the installed capacity of clean ARB compliant DG by an estimated 130 megawatts electrical (MWe).
- Achieves maximum CHP efficiency, exceeding 80 percent in most cases.
- Reduces GHG emissions by 0.17 to 0.26 tons/MWhr compared to power generation at modern and conventional central plants.
- Provides NO_x reduction capability for existing boilers while giving owners/operators an attractive ROI on their ULN investments.
- Reduces the cost and energy requirements for industrial/commercial boiler NO_x compliance with local air permits by reducing or eliminating the use of FGR and reducing the energy for combustion air supply.
- Minimizes the investment and maintenance cost of DG, improving the economic competitiveness of industrial and commercial steam plants.
- Provides off-grid boiler operation capability for reduced impact due to power outages.
- Can provide improved boiler standby capability for faster response to steam generating demand.

CHAPTER: Introduction

This project successfully demonstrated a new and more advanced combined heat and power (CHP) technology for small scale distributed generation (DG) in industrial and commercial plants. This technology builds on the energy savings of conventional CHP by developing a low NO_x emission simple cycle, unrecuperated, microturbine that is closely integrated with an ultra low NO_x (ULN) burner for retrofit on industrial and commercial boilers.

This section highlights the technology and commercial status of small scale CHP, the objectives of this project and key technical accomplishments.

1.1 Background

Large and small combined heat and power (CHP systems are widely seen as an important element of California strategy for achieving caps in greenhouse gas (GHG) emissions established in California Assembly Bill (AB) 32[1]. Large CHP systems with generating capacities of up to 25 megawatts electric (MWe) have been installed and used for many years as a highly efficient energy supply system to fulfill electricity and thermal energy needs in a wide range of applications around the world. These large CHP installations benefit from economies of scale. Small CHP systems, however, especially those with generating capacities of less than 250 kilowatts electrical (kWe) have seen limited acceptance due to various factors including cost, performance and reliability.

Conventional microturbine-based CHP packages with power generation less than 250 kWe consist principally of a recuperated microturbine or reciprocating engine equipped with a heat exchanger for generating hot water. The efficiency of these integrated CHP systems is typically limited to maximum of 70 percent (%) because of the sensible heat available in the turbine exhaust gas (TEG). Their applications are also limited to commercial sites where hot water is needed. In spite of the attractive energy efficiencies, these microturbine CHP packages have seen disappointing market penetration because high installed cost and excessive maintenance.

A more efficient type of microturbine-based CHP, however, consists of microturbine exhausting into an industrial burner for the generation of steam or chilled water. This second CHP approach can result in efficiencies approaching 80 percent because of the reburning of the microturbine exhaust. Though more efficient, these small CHP systems have also seen limited market penetration because commercial microturbine packages are not designed for these applications, and performance, ease of operation, cost and boiler emission compliance are thus not optimized.

Commercial and industrial boilers of the package design, with single burners, provide an ideal thermal sink for the waste heat from microturbines used in distributed generation (DG). When

[1] *Final Opinion and Recommendations on Greenhouse Gases Regulatory Strategies,* California Energy Commission and California Public Utility Commission, October 2008 .

coupled with an industrial boiler, the microturbine can be used without the conventional recuperator because industrial boiler furnaces are more efficient in recovering waste heat than conventional recuperators used in commercial CHP packages. In its unrecuperated design, microturbines become less costly, more compact, and require less maintenance greatly reducing the cost and complexity of these systems.

It is estimated that there are over 1,300 industrial package boilers operating in California and more than 30,000 nationwide[2]. The development of this market has the potential for thousands of clean, low-cost, and efficient megawatts electric (MWe) of DG while also providing significant benefits to the boiler owner/operator by reducing cost of boiler operation and emission compliance.

Because the CHP technology incorporates a ULN industrial burner, the integrated CHP developed in this project will also be able to provide incentives for replacement of higher polluting industrial burners currently in use, resulting in the dual benefit of reducing emissions from industrial boilers while also providing a return on investment (ROI) via energy savings available with CHP. These improvements are anticipated to address some of the current barriers to the deployment of small scale DG in small to medium industrial plants.

1.2 Scope

This project addresses these market deficiencies by focusing on the development of a truly packaged CHP assembly that combines the benefits of a simple MTG configuration integrated with a burner/windbox assembly that offers the compactness of current burner systems with the added benefit of DG. The capital cost of the MTG can be reduced by removing high-maintenance components, such as the recuperator, and embedding the core equipment inside a windbox assembly.

Therefore, the overall scope of the project was to integrate the core components of a low-cost unrecuperated microturbine generator (MTG) with the windbox of a Coen ultra-low NO_x (ULN) burner. By stripping away the expensive and maintenance-prone recuperator from a conventional MTG package, the core equipment of the MTG consisting of the air compressor, power turbine, combustor and generator were integrated with a modified burner windbox. The advantages of this arrangement are:

- Provide one packaged, integrated burner-combined heat and power (CHP) system sold and maintained by one vendor of industrial/commercial burner assemblies.
- Reduce the cost of the generator by eliminating the recuperator and auxiliary ducting and insulation.
- Eliminate most of the installation cost by integrating the MTG as part of the burner/windbox assembly.

[2] *Analysis of the Industrial Boiler Population*, Energy and Environmental Research, Report No. GRI-96/0200, June 1996

- Reduce the maintenance cost of the MTG by removing the high maintenance components of current systems.
- Recover radiation and convective heat losses associated with the MTG by immersing all high temperature components inside the combustion air stream feeding the boiler burner.
- Provide outside cooling of the compressor air charge to the premixed turbine combustor by placing the combustor in the flow of fresh incoming air.
- Increase the heat loading to the boiler to boost the thermal versus power utilization of fuel chemical energy.
- Provide greater flame stability to the burner for the boiler with combustion air preheat, thus permitting operation at lower equivalence ratios for ultra-low-NOx performance.
- Provide a steady rate of flue gas recirculation (FGR) to the ULN burner thus decreasing capacity needs for FGR fan.
- Eliminate the purchase of a larger air blower for the boiler normally associated with the installation of a new ULN burner

1.3 Project Objectives

The overall objective of this project was to develop and test a novel CHP package that integrates a simple cycle, unrecuperated, 80 kWe microturbine with a gas-fired ULN burner for package industrial and commercial boilers. The incentives for this new CHP development were that in this configuration the overall CHP efficiency can be maximized by recovering all waste heat; the cost of small-scale DG can reduced; the physical footprint can be minimized for ease of retrofit, and the cost of boiler emission compliance can be reduced.

Specifically, the project had the following performance objectives:

1. Maximize overall CHP efficiency to a minimum of 80 percent;
2. Comply with the California Air Resources Board (ARB) 2007 emission requirements for DG by reducing simple cycle microturbine NO_x to less than 5 ppm, corrected to 15 percent O_2;
3. Comply with applicable air permit levels for industrial boilers that are retrofit with this new CHP technology; and
4. Reduce the cost of small-scale DG in CHP configuration to $700/kWe.

Low NO_x emissions from the MTG are necessary to minimize the overall emissions from the CHP as measured at the boiler stack. This is because microturbine NOx emissions are additive to NOx formed in the boiler. Thus, excessive microturbine NOx in the turbine exhaust gas (TEG) can impact on the ability to comply with local permit limits for new or retrofit industrial boilers.

1.4 Organization and Responsibilities

The work responsibilities for this test project were as shown below:

- CMC-Engineering assumed the overall project management and principal engineering roles leading the development of a new silo combustor technology for simple cycle microturbines and the design of the integrated CHP package.
- Lawrence Berkeley National Laboratory (LBNL) and Calnetix were contracted to design, fabricate and test the low-NOx silo combustor design. Tests were performed in the laboratory and on an engine test cell.
- Calnetix Power Solutions (CPS) engaged in the design of a new turbine housing design to adapt the new silo combustor and made available their test facilities for final demonstration of the new combustor.
- Coen was contracted to design, fabricate and test the integration of the modified simple cycle microturbine to achieve optimum operational synergy with selected ULN burner.
- Coen was also contracted to retrofit and test the completed CHP assembly on a packaged watertube boiler located at an industrial steam plant in California.
- Project coordination and reporting, including this final report, were performed by CMC-Engineering.

The CHP technology also targets potential benefits to be derived from the MTG exhaust that provides hot vitiated air, that when properly mixed with the incoming burner air, can assist in suppressing NO_x formation in the ULN burner and improve flame stability. The other objectives focus on the CHP hardware configurations that maximize waste heat recovery and minimize overall investment cost.

1.5 Results Summary

Table 1 lists the key project results and technical achievements. The project achieved all its objectives and a new type of CHP assembly and application was field demonstrated.

1.6 Relationship to PIER Goals

CHP is an important component in the portfolio of technologies considered for California attainment of energy efficiency and GHG reduction goals. The widespread use of this technology can significantly contribute to statewide reductions in natural gas consumption used in the generation of electricity by reducing the cost of such systems; improving prime mover waste heat recovery; improving boiler performance and energy utilization; and facilitating commercialization of small-scale distributed generation for industrial and commercial CHP markets. With these energy efficiency gains, GHG emission reductions are also achieved.

Therefore, this project supports PIER program objectives in the area of:

- Improving the energy cost/value of California electricity by reducing the electrical power cost for public and private sectors, increasing the electricity capacity within the state, and enhancing the state's power infrastructure.
- Reducing the cost and improve efficiency of environmentally compliant CHP technologies to facilitate the commercial deployment of energy-saving CHP that reduce energy demand, lower fuel costs, reduce CO_2 emissions, and improve competitiveness for California industry.

Reducing the carbon footprint of power generation in the California is in line with AB 32 goals for implementing an aggressive strategy for CHP implementation and reducing GHGs.

Table 1: Key Project Results and Achievements

Project Objective	Technical Approach	Technical Innovation	Results
Reduce cost of conventional CHP	Select microturbine for simple cycle CHP application	CHP is based on low cost, low-maintenance simple cycle microturbine	Selected Elliott microturbine for ease of simple cycle configuration
Reduce NO_x emissions for a simple cycle microturbine to comply with CARB 2007 CHP limits	Use a newly designed and tested recuperated silo design with LBNL low swirl combustor nozzle (LSN)	New fully-premixed silo combustor	Achieved 3 ppm NO_x in simple cycle firing configuration, minimizing NO_x contribution to boiler emissions
Recover all the waste heat from microturbine for maximum fuel energy recovery	Design an integrated package allowing exhaust and convective heat losses to be fully recovered in the boiler	Newly designed microturbine enclosure with partition of hot section for ease of heat recovery	Achieved 100 percent waste heat recovery from the microturbine resulting in power conversion efficiencies of nearly 100% (LHV)

Project Objective	Technical Approach	Technical Innovation	Results
Optimize industrial burner NO_x performance with hot temperature simple cycle microturbine exhaust	Perform detailed flow mixing and temperature characterization with effect on ULN burner NO_x and turndown capability	Newly designed bustle to channel microturbine exhaust for Coen QLN™ burner	Achieved improved performance of Coen QLN burner with higher FGR rates and improved combustion stability
Integrate microturbine and boiler operation for optimum efficiency and safe operation	Reconfigure Coen Burner Management System (BMS) and provide safeguards	Introduced new equipment, sensors, and controls	Demonstrated operation and identified requirements for fully automatic operation
Select and retrofit a test site to demonstrate the technology	Locate flexible host facility and obtain permits and agreements	First application of simple cycle microturbine-burner CHP integrated assembly	Achieved emission permit levels and CHP efficiency objectives

CHAPTER 2: Project Approach

The overall project was divided into twenty separate tasks, seventeen technical tasks and three additional tasks, one for project management and two support tasks. The technical tasks, starting with Task 2 and ending with Task 18 as shown in Table 2 focused on engineering hardware development and testing activities. The early tasks of the project focused on the selection of key hardware components that will form the CHP assembly, and on the design requirements that will be used to achieve the performance objectives for the proposed CHP technology. An Elliott microturbine available in a Bowman package was selected because of its availability as a simple cycle unit. Coen portfolio includes several ULN burner designs. Therefore, the integration of the microturbine exhaust was targeted to be applicable to each burner type as selection of the burner technology can vary from site to site according to several factors including local air permit requirements and types of fuels. The selections of the microturbine, burner windbox, and ULN burner were then used to identify modifications necessary to each component to achieve the design and performance objectives of the project. Tasks 2 to 4 target hardware selection and preliminary process configuration. Tasks 5 to 14 focused on the modification to this hardware and preliminary testing to support the modifications to individual components and finalize the CHP assembly design. Finally, Tasks 15 through 18 targeted the final field demonstration. The selection of the host site boiler available for retrofit provided the final design details for the final CHP configuration based on the required ULN burner, air permit levels, backup fuels, and boiler capacity.

The following subsections present the approach specific to each of seventeen technical tasks and two additional support tasks required under the contract agreement with the Energy Commission.

2.1 Task 2 Select Coen Burner and Windbox Assembly

The goal of this task was to select the burner/windbox assembly from available Coen design that represents the most readily adaptable arrangement and performance needs for the proposed CHP. The windbox was to be modified based on the design and operation of the burner selected. This task focused at the adaptation of Coen QLN™ and QLA™ burners, which can be better suited to higher volumes of high temperatures combustion air and flue gas because of the optimization in pressure drop.

The project approach specific to this task included the following:

- Prepare the List of Performance Objectives and Operational Attributes of the CHP System.
- Prepare an Outline of the Burner Hardware Requirements that are compatible with the performance objectives of the proposed CHP (i.e., air temperature, resistance to flameouts, FGR capability, etc). There will not be a draft and final of this deliverable.
- Select likely configuration for MTG, including combustor arrangement.

- Select burner control system that will need adaptation and integration with Bowman turbo-alternator control.

Table 2: List of Project Technical and Administrative Tasks

Task	Title	Approach
1	Administration	Secure subcontractors and technical support and monitor progress
2	Select Coen Burner and Windbox Assembly	Review Coen ULN burner operating requirements and windbox design for retrofit and modifications
3	Develop Fluent Model of Windbox Assembly	Select possible MTG retrofit configurations and TEG channel and evaluate process flows using computational modeling
4	Perform Engineering Analyses	Develop energy and mass balance process data to determine TEG waste heat recovery approaches
5	Integrate MTG and Burner Controls	Highlight requirements for burner and MTG interface controls necessary for burner only and CHP operation
6	Engineer Insulation and Acoustic Control	Evaluate requirements for heat loss control and noise abatement
7	CHP prototype Design	Develop drawings for first prototype CHP design
8	Silo Combustor for Simple Cycle Microturbine	Design and fabricate an new combustor for sub 5 ppm NO_x performance out of the microturbine
9	Assemble and Pre-Test Silo Combustor	Perform laboratory testing to validate operating requirement for premixed lean combustor
10	Fabricate, Assemble and Pre-Test Prototype Unit	Fabricate final combustor and perform tests on microturbine test cell to validate and optimize design
11	Develop Prototype Test Plan	Draft a test plan for the ULN burner integrated with a simple cycle microturbine
12	Perform Prototype Testing	Conduct tests at Coen research facility to obtain CHP performance data and operating limits
13	CHP Standard Arrangement	Finalize CHP configuration and prepare final engineering and construction design
14	Develop Costing	Evaluate the added capital cost of adding a power generator in the final CHP assembly

Task	Title	Approach
15	Secure Field Host Site	Secure agreement and air permits for the selected host site
16	Fabricate, Install and Checkout Field Test Unit	Select ULN for host site. Fabricate burner and auxiliary parts. Ship all equipment. Modify facility and install and commission CHP assembly
17	Develop Field Test Plan	Draft a field test plan to determine air permit compliance and energy savings
18	Perform Field Testing	Conduct a series of measurements to confirm emission compliance and performance
19	Technology Transfer	Present progress of the development at conferences and meetings
20	Commercialization Plan	Develop a commercialization plan to assist Coen in offering the technology to commercial clients

- Make selection of optimum burner/windbox based on necessary modifications, key performance objectives, and cost.
- Prepare the Burner/Windbox Selection Report. This report shall include, but not be limited to, the following:
    - The likely configuration for MTG, including combustor arrangement;
    - The selected burner control system and a discussion of the factors that led to this selection over alternatives;
    - The selection of the Burner/Windbox and a discussion of the factors that led to this selection over alternatives.

2.2 Task 3 Develop FluentTM Model of Windbox Assembly

The goal of this task was to prepare a flow model of the windbox and burner assemblies with the placement of the MTG and evaluate several arrangements to optimize the flow, mixing, pressure losses, and overall dimensions. The placement of the MTG into the windbox, shortly upstream of the burner throat, affects the combustion airflow patterns to the burner. Because of the requirements for ULN premix operation, the objective was to maintain adequate distribution of combustion air over the entire front of the burner.

The project approach specific to this task included the following:

- Prepare a CFD Model using Fluent™.
- Develop several preliminary key component arrangements.

- Develop flow patterns, velocity vectors and heat transfer profiles for each arrangement.
- Make additional evaluations based on different capacity ratios in CHP system.
- Identify optimum configuration and minimum hardware and operating requirements.
- Prepare the Fluent™ Model of Windbox Assembly Report. This report shall include, but not be limited to, the following:
    - The goal of this task;
    - The description of the approach used;
    - List of activities performed;
    - Description of the results and to what degree the goal was achieved;
    - Significant issues encountered and how they were addressed;
    - A discussion of the implications regarding the success or failure of the results, and the effect on the budget and the overall objectives of the project;
    - Flow modeling grids;
    - Flow patterns for each configuration;
    - Key design and operating parameters for each configuration; and
    - List of potential hardware improvements to existing Coen burner/windbox assembly.

2.3 Task 4 Perform Engineering Analyses

The goal of this task was to complete the final engineering analyses of the prototype CHP for mass flow, heat transfer, pressure drops, auxiliary power needs, combustion stability, FGR requirements, burner turndown, NO_x formation, shutoff and shutdown sequences, etc.

The project approach specific to this task included the following:

- Develop a mass and energy balance for the prototype CHP.
- Perform structural analyses.
- Calculate trends in design, size, and configurations versus key engineering and performance specifications.
- Prepare the Engineering Analyses Report. This report shall include, but not be limited to, the following:
    - The goal of this task;
    - The description of the approach used;
    - List of activities performed;
    - Description of the results and to what degree the goal was achieved;
    - Significant issues encountered and how they were addressed;
    - A discussion of the implications regarding the success or failure of the results, and the effect on the budget and the overall objectives of the project;

- Engineering specifications of the prototype unit;
  - Engineering specifications of two other CHP-burner systems with different thermal capacities; and
  - Final configuration and ASTM, ASME, and ABMA code compliance.

2.4 Task 5 Integrate MTG Controls and Burner Controls

The goal of this task was to develop the control logic diagram, software, and integrated control system for the operations of the MTG in conjunction with the boiler burner, FGR fan, steam pressure, and other auxiliary equipment.

The project approach specific to this task included the following:

- Develop the logic diagrams.
- Develop safety control loops.
- Design an integrated control system and electronic assembly.
- Prepare the Control System Design Report. This report shall include, but not be limited to, the following:
  - Logic diagrams; and
  - Description and discussion of the control system design.
- Fabricate the system.
- Test and checkout the system and procure ANSI testing certification.
- Prepare the Control System Test Report. This report shall include, but not be limited to, the following:
  - Test results;
  - Analysis;
  - Conclusions;
  - Recommendations; and
  - Photographs as appropriate.

2.5 Task 6 Engineer Insulation and Acoustic Control

The goal of this task was to evaluate and design the necessary insulation and acoustic controls for the windbox and burner assembly. These are necessary because of the increase in combustion air temperature with the CHP configuration and the needed FGR rates. The degree of thermal insulation will be in relation to the ratio of electricity generation and power output. Sound insulation will be necessary to maintain regulatory limits on dB levels at fixed distance from the unit.

The project approach specific to this task included the following:

- Calculate the amount of thermal insulation needed.
- Estimate the decibel (dB) level.

- Estimate vibration and other potential harmonic-induced acoustics.
- Design the acoustic and thermal insulation arrangement.
- Provide the Commission Contract Manager with the Thermal and Acoustic Protection System Designs and Specifications. There will not be a draft and final of this deliverable.

2.6 Task 7 CHP Prototype System Design

The goal of this task was to prepare a completed set of line drawings and P&ID for the proposed CHP prototype to be fabricated and tested at the Coen facility in Burlingame, CA. Coen led the design effort with CAD support. The project team was to have all the engineering and design data necessary to build the integrated burner-CHP package with all the auxiliary equipment and integrated control system. The team focused on the design for a unit with 80 kWe electricity generation and a thermal load of 10 to 30 MMBtu/hr.

The project approach specific to this task included the following:

- Take the preliminary design inputs from the MTG, windbox, burner, and needed auxiliary CHP and boiler components and prepare a detailed set of line drawings for each component and fabrication assembly drawings.
- Prepare the CHP Prototype System Design Report. This report shall include, but not be limited to, the following:
    - The goal of this task;
    - The description of the approach used;
    - List of activities performed;
    - Description of the results and to what degree the goal was achieved;
    - Significant issues encountered and how they were addressed;
    - A discussion of the implications regarding the success or failure of the results, and the effect on the budget and the overall objectives of the project;
    - Complete set of line drawings for each component;
    - Control logic and operation;
    - P&ID for fuel and power connections; and
    - Complete set of specifications for each component.

2.7 Task 8 LSB for Bowman Turbo-Alternator

The goal of this task was to incorporate LBNL LSB and LSN technologies in a prototype combustor for the Bowman turbo-alternator. In its vendor-supplied configuration the Bowman MTG was equipped with a high NO_x burner and ring combustor assembly. LBNL successful LSN was utilized for a new ultra low NO_x (<5 ppm) combustor. An 80 kWe simple cycle microturbine was purchased from Bowman.

The project approach specific to this task included the following:

- Select optimum combustor configuration (silo, annular).

- Design the LSN and premix assembly based on ongoing Solar Turbines testing.
- Configure and fabricate components for parametric testing.
- Prepare the LSB Turbo-Alternator Report. This report shall include, but not be limited to, the following:
  - the goal of this task;
  - the description of the approach used;
  - list of activities performed;
  - description of the results and to what degree the goal was achieved;
  - significant issues encountered and how they were addressed;
  - a discussion of the implications regarding the success or failure of the results, and the effect on the budget and the overall objectives of the project;
  - LSN and combustor design configuration;
  - System and component drawings.

2.8 Task 9 Assemble and Pretest a LSB Combustor at the LBNL

The goal of this task was to perform parametric testing with these combustors/LSB assemblies at LBNL bench scale facilities for the purpose of validating combustion stability, acoustics, and NO_x and CO emissions. This task provided the performance validation necessary to go ahead with the integration of the system into the Coen windbox-burner assembly in Task 10.

The project approach specific to this task included the following:

- Set up test facility at LBNL.
- Prepare the LSB Combustor Test Plan. This plan shall include, but not be limited to, the following:
  - Description of the test apparatus;
  - Description of the combustor design and nozzle assembly;
  - Compression ratios;
  - Light-off and firing rates;
  - Test duration; and
  - Emissions measurements, instrumentation, and methods.
- Perform testing of the combustor in accordance with the Final LSB Combustor Test Plan.
- Confirm performance levels for NOx and CO.
- Prepare the LSB Combustor Test Report. This report shall include, but not be limited to, the following:
  - Test data to support the performance guarantees of <5 ppm NOx and <20 ppm CO;
  - Test data to support combustion stability and stable operation at low equivalence ratio (high air/fuel ratio consistent with low NOx operation);

- Final design for combustor and premix nozzle assembly for Bowman turbo-alternator;
- Other test results;
- Analysis;
- Conclusions;
- Recommendations; and
- Photographs.

2.9 Task 10 Fabricate, Assemble and Install a Test Unit

The goal of this task was to assemble all the engineered components of the CHP system at Coen facility in Burlingame, CA. The system was to be complete in all key and auxiliary components to mimic the operation in a full-scale facility. This performance was needed for achieving the overall emission goals of the CHP system. Coen led the fabrication and installation effort.

The project approach specific to this task included the following:

- Fabricate all required burner parts for the CHP. These will likely include:
  - Modified windbox;
  - Fan motor and fan wheel assembly;
  - Structural support for MTG;
  - Fuel lines, meters, and connectors;
  - Modified burner;
  - Thermocouple and pressure sensors;
  - Integrated FYR™ control system.
- Obtain necessary permits and cooperate with the lead agency's CEQA review for the prototype testing.
- Submit copies of air quality permits and any documents prepared pursuant to CEQA, to the Commission Contract Manager.
- Assemble all the components of the prototype CHP.
  - MTG from Bowman;
  - LSN and combustor system for the MTG from LBNL;
  - Windbox and FGR assembly, Coen low NOx premix burner;
  - Combustion air fan; gas compressor for MTG; and integrated control system.
- Install the completed CHP prototype system on the test yard firetube boiler.
- Connect to the local power grid at Coen's facility.
- Perform preliminary startup and system checkout.
- Report on all of the activities in this task in the Monthly Progress Reports.

2.10 Task 11 Develop Test Plan for Prototype Unit

The goal of this task was to prepare a test plan for the validation of the performance of the CHP burner/windbox assembly at the Coen's test yard in Burlingame, CA. The test matrix addressed all the performance specifications and measurements of efficiency, heat loss, emissions, turndown, FGR requirements, and auxiliary power needs. The test matrix addressed applicable measurements and protocols to ensure a consistent set of performance data and emissions to be compared with other DG equipment.

The project approach specific to this task included the following:

- Prepare the Prototype Unit Test Plan. This test plan shall include, but not be limited to, the following:
  - Description of test facility and equipment;
  - Test matrix of kWe, thermal load input, excess combustion air, FGR rates, etc.; and
  - List of measurements:
    - O_2, CO_2, CO, NO_x and in the windbox and at the boiler stack;
    - Noise levels;
    - Natural gas flow to MTG and burner;
    - Combustion air flow added to the windbox;
    - Temperature and pressure in the windbox;
    - kWe power output and power quality; and
    - Planned calculations for MTG efficiency, boiler efficiency and CHP efficiency.

2.11 Task 12 Perform Prototype Testing

The goal of this task was to perform the testing of the prototype CHP system according to the prototype test plan developed in Task 11. The objective of the tests was to validate efficiency, emissions, and compliance with standard design and operating practices of burners for the industrial/commercial boiler operation, thus ensuring readiness for field application.

The project approach specific to this task included the following:

- Conduct the testing of the prototype CHP unit in accordance with the prototype unit test plan.
- Monitor and record key operating data to calculate fuel utilization performance, electricity delivery and quality, heat balance, emissions from the MTG and from the boiler burner, and operational flexibility.
- Perform all needed calculations.
- Prepare the draft prototype unit test report. This document. This document shall include, but not be limited to, the following:

- Raw test data (boiler, MTG, fuel use, emissions, noise, power and quality, combustion air, FGR rates, windbox O_2, temperature, and pressures);
  - Reduced test data (emission rates, system efficiency, total energy use, total energy output, ASME heat loss and input/output calculations, trends, etc.);
  - Other test results;
  - Analysis;
  - Conclusions;
  - Recommendations; and
  - Photographs.
- Prepare the critical project review (CPR) report.
- Participate in the CPR meeting.

2.12 Task 13 Standard Arrangements

The goal of this task was to finalize the standard arrangements for the CHP system based on the demonstrated performance of the CHP system during the test yard tests. This entailed revisiting the performance of individual components and making necessary improvements to the design, arrangement and hardware, if needed. This task finalized the commercial version for the prototype CHP system.

The project approach specific to this task included the following:

- Evaluate test yard performance.
- Recommend improvements (if needed).
- Specify new set of standard arrangements and component specifications.
- Finalize line drawings.
- Prepare the Standard Arrangements Report. This report include the following:
  - The goal of this task;
  - The description of the approach used;
  - List of activities performed;
  - Description of the results and to what degree the goal was achieved;
  - Significant issues encountered and how they were addressed;
  - A discussion of the implications regarding the success or failure of the results, and the effect on the budget and the overall objectives of the project;
  - Final set of line drawings; and
  - Final equipment specifications.

2.13 Task 14 Develop Costing

The goal of this task was to develop a bottom-up costing of the CHP system and to compare that cost to the baseline costs of conventional packaged boiler burners being sold by Coen and conventional modular CHP assemblies.

The project approach specific to this task included the following:

- Develop detailed list of components;
- Develop line item costing;
- Compute total cost of CHP system prototype;
- Gather the cost of conventional CHP modular systems from recent installations;
- Perform a common-basis cost comparison;
- Detail the incremental cost of DG in the prototype CHP;
- Detail the cost of electricity based on the added investment for the power generation option in the CHP system and the fuel utilization efficiency demonstrated in the testing;
- Prepare the Costing Report. This report shall include, but not be limited to, the following:
  - The goal of this task;
  - The description of the approach used;
  - List of activities performed;
  - Description of the results and to what degree the goal was achieved;
  - Significant issues encountered and how they were addressed;
  - A discussion of the implications regarding the success or failure of the results, and the effect on the budget and the overall objectives of the project;
  - Detailed costing;
  - Incremental investment and operating cost of power generation in industrial/commercial/institutional steam generation; and
  - Cost benefit analysis.

2.14 Task 15 Secure Field Host Site

The goal of this task was to identify, secure, and coordinate field test arrangement with a host facility in California for demonstration of the CHP system. The targeted facility was to have a boiler in the 10 to 30 MMBtu/hr firing capacity and a typical industrial load cycle.

The project approach specific to this task included the following:

- Visit and propose a demonstration test at a facility
- Negotiate cost of retrofit.
- Negotiate leave-in-place or return to original condition clauses.
- Enter into an agreement with the selected site owner to address such issues as:

- Details of the test, including dates, length of test;
    - Site owner input and feedback on test conditions;
    - Access to site;
    - Insurance and indemnity;
    - Contingency if damages are caused by test; and
    - Equipment installation and removal.
- Obtain necessary permits and cooperate with the lead agency's CEQA review for the field test.
- Submit copies of air quality permits and any documents Energy Commission
- Investigate grid-hookup requirements and charges.
- Draft and execute applicable contracts and indemnification agreements.
- Secure a retrofit schedule.
- Obtain agreements on test duration, site visits, and other factors.
- Report on all of the activities in this task in the Monthly Progress Reports.

2.15 Task 16 Fabricate, Install and Checkout Field Test Unit

The goal of this task was to fabricate a CHP system that matched the capacity and hardware requirements of the selected host site. The MTG used in the prototype system was used for the field installation because of the fixed generating capacity of 80 kWe provided by Bowman. Other elements of the CHP system were optimized to reflect the retrofit needs of the selected site.

The project approach specific to this task included the following:

- Fabricate or modify hardware to match the thermal load of the host facility.
- Reassemble components.
- Ship equipment to the site.
- Remove existing burner/windbox assembly.
- Install new CHP/burner system.
- Install power conditioning and grid hookup.
- Perform preliminary startup and system checkout.
- Report on all of the activities in this task in the Monthly Progress Reports.

2.16 Task 17 Develop Field Test Plan

The goal of this task was to develop detailed draft and final test plans for the field demonstration.

The project approach specific to this task included the following:

- Prepare the Field Test Plan according to the ASERTTI protocols developed under US Department of Energy Contract DE-FC36-02GO12017, "Collaborative National Program for the Development and Performance Testing of Distributed Power Technologies with Emphasis on Combined Heat and Power Applications." Constraints that may hinder full compliance with these protocols include, but are not limited to, the following: budget, schedule, relevance to microturbine prime mover, and/or the availability of specialty measurements and testing devices. This plan also included the following:
    - Description of the host site and energy requirements;
    - Description of the boiler and burner-CHP system;
    - Description of the power purchase agreement between the field test host site and the utility providing power to the site. Such an agreement may not be needed if the test host site is able to use all of the power produced by the field test unit because no power would be exported to the utility's grid;
    - Test matrix detailing all planned full load and part load tests; and
    - FGR and combustion air flowrates.

2.17 Task 18 Perform Field Testing

The goal of this task was to perform the field-testing of the commercial prototype unit at the selected host facility. The tests covered both short-term parametric testing and simulation of fully unattended operation.

The project approach specific to this task included the following:

- Secure and bring appropriate field test equipment including acoustic, power quality, and fuel flow sensors and emission monitoring to the site.
- Install needed monitors.
- Perform the parametric testing.
- Collect field test data.
- Perform onsite data evaluation.
- Arrange for data collection.
- Perform off-site data analysis of short-term parametric data.
- Collect long-term data remotely.
- Perform selected visits to ensure proper operation.
- Prepare the Field Test Report. This report shall include, but not be limited to, the following:

    - Complete set of test data (short- and long-term);
    - Test results;
    - Analysis;
    - Conclusions;
    - Recommendations, including recommendations for leaving equipment in place or returning site to original condition; and
    - Photographs.

2.18 Task 19 Technology Transfer Activities

The goal of this task was to develop a plan to make the knowledge gained, experimental results and lessons learned available to key decision-makers.

The project approach specific to this task included the following:

- Prepare a Technology Transfer Plan. The plan shall explain how the knowledge gained in this project will be made available to the public. The level of detail expected is least for research-related projects and highest for demonstration projects. Key elements from this report were included in this final report for this project; and
- Conduct technology transfer activities in accordance with the Technology Transfer Plan. These activities shall be reported in the Monthly Progress Reports.

2.19 Task 20 Production Readiness Plan

The goal of the plan is to determine the steps that will lead to the manufacturing of the technologies developed in this project or to the commercialization of the project's results.

The project approach specific to this task included the following:

- Prepare a Production Readiness Plan. The plan included, as appropriate, but not be limited to:
    - Identification of critical production processes, equipment, facilities, personnel resources, and support systems that will be needed to produce a commercially viable product;
    - Internal manufacturing facilities, as well as supplier technologies, capacity constraints imposed by the design under consideration, identification of design critical elements and the use of hazardous or non-recyclable materials. The product manufacturing effort may include "proof of production processes;"
    - A projected "should cost" for the product when in production;
    - The expected investment threshold to launch the commercial product; and
    - An implementation plan to ramp up to full production.

2.20 Project Phases

The work in these nineteen tasks was grouped into five separate phases that target the fur key technical objectives of the project and supporting activities. These phases are described below:

Phase I.	Development and Testing of a Low-NOx Silo Combustor
Phase II.	Design and Fabrication of Microturbine-Burner Interface
Phase III.	Assembly of Integrated CHP Components
Phase IV.	Field Installation and Testing
Phase V.	Support Technical Activities

Phase I includes work performed under Tasks 8, 9 and 12. During this phase,, a simple cycle microturbine was selected and purchased for the upgrade to a first-of-a-kind ultra-low NOx simple cycle engine capable of meeting California Air Resources Board (ARB) 2007 emission requirements of 0.07 pounds per megawatt-hour (lb/MWhr) for distributed generation (DG) in CHP configuration. Also in this Phase I, work was initiated at Lawrence Berkeley National Laboratory (LBNL) on the design, fabrication and laboratory testing of a new fully premixed silo combustor. The combustor incorporated an LBNL proprietary premix low swirl nozzle (LSN), also known as the low swirl burner (LSB). The successful testing of first prototype and final design of the silo combustor on a test cell at Calnetix Power Solutions (CPS) in Stuart, Florida concluded the work during this Phase of the project.

Phase II includes work performed under Tasks 2 through 7 and Task 10. During this phase, work at Coen was initiated by addressing the available options for integrating the hot exhaust (1,050° Fahrenheit [F]) from the microturbine with a standard Coen windbox and ULN burner in such a way to promote burner stability at low NO_x, recover all the waste heat from the microturbine and secure operational flexibility and safety for the owner/operator . Therefore, during this Phase II, Coen selected a ULN burner from their portfolio of commercial burners; performed computational fluid dynamics (CFD) modeling of effect of microturbine exhaust and mixing methods on burner performance; and designed and fabricated a microturbine enclosure and microturbine-burner interface.

Phase III includes work performed under Tasks 11 through 14. During this phase, the project team assembled a prototype fully integrated CHP system and performed preliminary tests to establish the impact of hot microturbine exhaust on ULN performance and develop system integrating design. This effort was followed by initial system component assembly focusing on the new enclosure for the simple cycle microturbine. Also during this phase, estimates of cost for fully assembled CHP system based on the selection of a host site and boiler for retrofit of the technology. This work also and evaluation of the cost and cost-savings associated with the operation of the boiler with and without the MTG option.

Phase IV includes the work performed under the remaining technical Tasks 15 through 18. During this phase of the project, work focused on the field retrofit of the boiler, which included: site selection, securing of field test agreements and air permit, fabrication and installation of complete CHP system for retrofit on the selected boiler, drafting test plan, and performing field testing. The work also included the site-specific cost-benefit analysis of the CHP package to assist the host site in volunteering the site for this demonstration.

Finally, Phase V includes the work performed under Task 19 and 20 which focused on technology transfer activities performed throughout the project and preparing conclusions on the commercialization readiness of the CHP technology

CHAPTER 3:
Results

This section presents the results achieved in each of the five project phases described above. Appendix A in Section 6 provides a task by task detailed description of results.

3.1 Development and Testing of Low-NOx Silo Combustor

The three principal activities of this phase of the project were to: (1) select a microturbine in simple cycle configuration to minimize cost to the overall CHP assembly; (2) evaluate NO_x emissions implications for a CHP assembly; (3) develop a new low NO_x silo combustor for a simple cycle engine operating with ambient temperature air and higher fuel/air ratio than conventional recuperated engines; and (4) demonstrate performance and attainment of project emission goals. The following subsections highlight the results of these activities.

3.1.1 Elliott T-80 Simple Cycle Microturbine Design and Performance

An Elliott T-80 simple cycle microturbine was selected and purchased for the project. Elliott was since acquired by CPS. Figure 1 is a photograph of the microturbine and generator still on the receiving pellet. The microturbine and generator combination has an overall length of 28 inches. When it was purchased, this particular engine was rated at 80 kWe gross output at ISO standard conditions, although the same engine and generator are currently rated by CPS at 105 kWe gross output. This is because the 80 kWe rating is based on the engine rotating at 68,000 rpm, whereas the 105 kWe output is achieved with an 80,000 rpm rotational speed. CPS has since phased out the 80 kWe capacity engine.

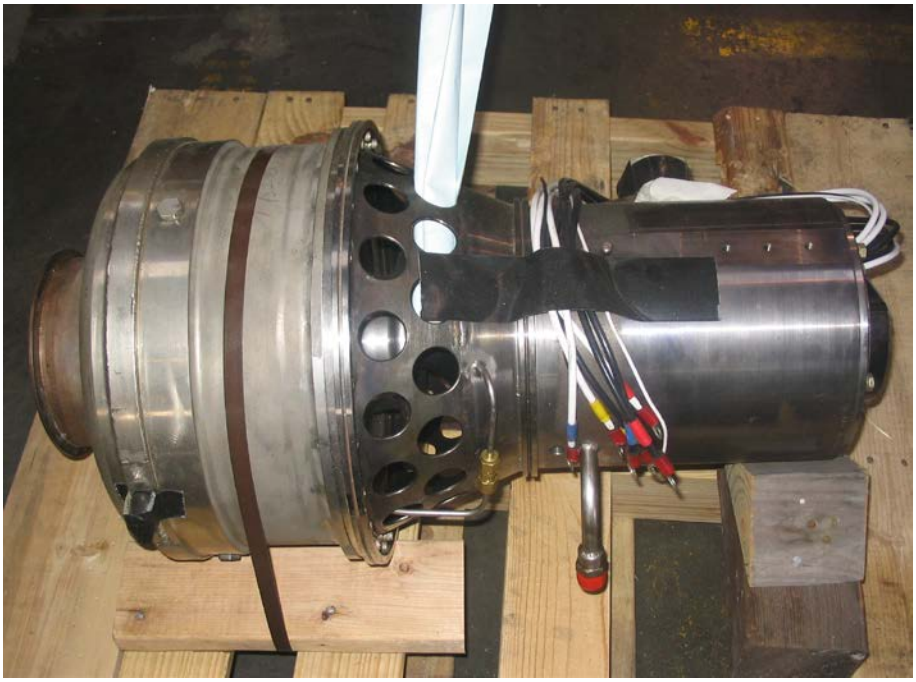


Figure 1: Pre-modified Elliott T-80 microturbine

The CPS T-80 and T-100 microturbines are equipped with a staged, partial oxidation, annular combustors of the type illustrated in Figure 2. A set of 12 gas nozzles inject fuel in a first stage where a portion of the combustion air burns the fuel under partial oxidation conditions. The remaining combustion air enters through a set of mixing holes and slots to complete combustion. Although the concept of staged combustion can be a valid approach in achieving low NO_x emissions, in a gas turbine the time available between first and second stages is much too small to prevent added NO_x formation in the second stage. Therefore, NO_x emissions tend to be high. This is illustrated in Figure 3 which shows baseline NO_x emissions for this microturbine in a simple cycle configuration tested for this project on a CPS test cell in Stuart FL. As indicated, NO_x emissions peaked at 25 ppm at part load and about 18 ppm at full load indicated by and an exhaust gas temperature (EGT) of 1,020° F. All emissions are reported corrected to 15 percent dry excess O_2. Because these NO_x emissions were about 10-fold too high for compliance with ARB 2007 DG requirements, it was necessary to replace the staged combustor with a newly designed low NO_x combustor. The project selected a fully premixed silo combustor design for this development.

Figure 2: Conventional CPS microturbine staged air combustor

3.1.2 Design and Fabrication of Prototype and Final Silo Combustor

Figure 4 shows how the integration of an 80 kWe MTG with a 50 million Btu per hr (MMBtu/hr) boiler will increase the regulated NO_x emissions from the boiler. The results are based on adding NO_x from the microturbine to the additional NO_x formed in the boiler flame. This additive effect is most likely as little or no NO_x reburning is anticipated by passing turbine exhaust gas (TEG) through the ULN burner. If the MTG emissions are excessive, the addition of a microturbine integrated with a boiler can have important negative implications on the permitting of the ULN burner. This is especially the case for some air districts in California that mandate NO_x limits as low as 9-ppm corrected to 3 percent O_2 dry. For example, an unmodified

80-kW MTG emitting about 20 ppm at 15 percent O_2 would add nearly 3 ppm to the overall NO_x emissions measured form a 50 MMBtu/hr boiler. This contribution would increase to 6 ppm if the boiler has a capacity of 25 MMBtu/hr. If the boiler were permitted at 9 ppm, the MTG emissions would amount to about 30 to 66 percent of the overall NO_x permitted even though the firing rate for the MTG is considerably lower than that of the boiler. Therefore, one of the key challenges of this project was to develop a new combustor that would address the NOx formation in the MTG so that the overall impact on the total boiler NO_x emissions would be negligible. The target NO_x levels from the MTG was set at less than 5-ppm , corrected to 15 percent O_2 which would add less than 1 ppm to the boiler emissions in most CHP applications .

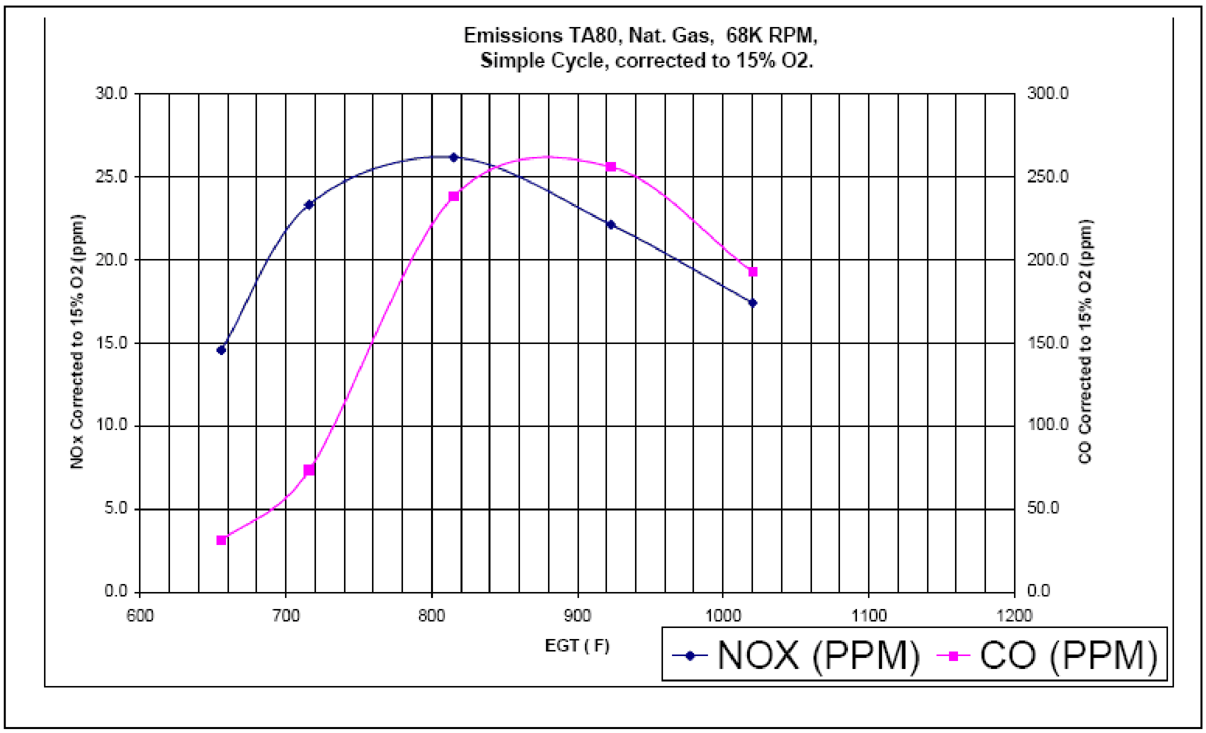


Figure 3: Baseline NOx and CO emissions from conventional combustor

A premixed silo combustor design was selected for the new microturbine combustor development. The selection is logical as premixed combustors are the basis of most dry low-NO_x combustors used in utility size turbines. Figure 5 illustrates the overall design approach that was selected to develop a new low NO_x microturbine combustor. Key components of the design are highlighted in Figure 5. As indicated, the LBNL LSB nozzle with its low swirl spinner vanes and perforated plate was used as the flame stabilizer technology selected for this new combustor. Compressor discharge air travels up outside the circumference of the inner liner, makes a U-turn and splits between primary and secondary air. The primary air travels in the center and premixes with the injected natural gas in the LSB nozzle. The premixed charge travels a distance through a mixing tube before igniting in the diverging section of the shroud where the flame anchors with a balance between flame speed, exit tube velocity and turbulence.

The secondary air bypasses the combustion zone providing accurate air/fuel control for the flame and film cooling for the hot surfaces of the shroud, ignitor, and liner.

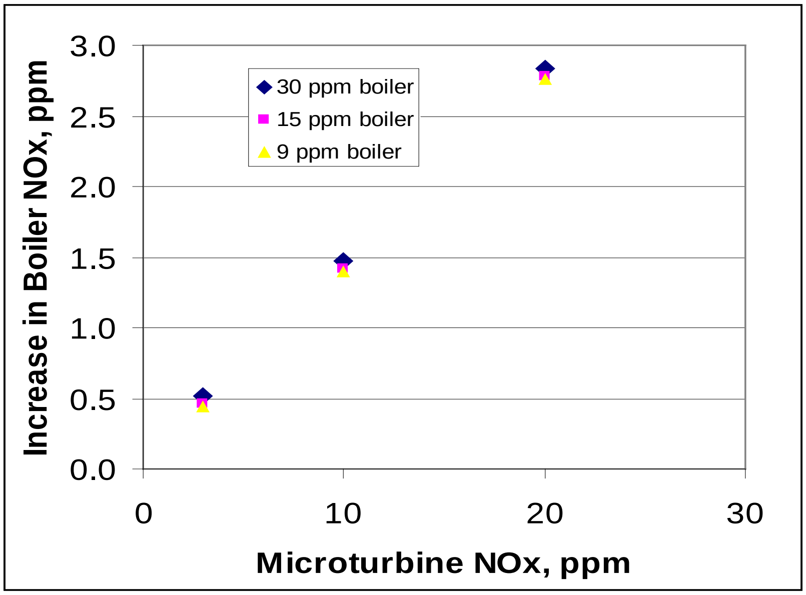


Figure 4: Impact of Microturbine NOx on Boiler NOx Emissions

One of the critical design requirements for the new combustor is the equivalence ratio (defined as the actual fuel /air ratio divided by the theoretical fuel-air ratio) in the primary combustion zone. The equivalence ratio is dictated by the target NO_x and CO emissions and combustion stability required at engine design load as well as during light-off and part loads. Figure 6 illustrates laboratory test results of NO_x versus equivalence ratio for the combustor. These data, which are representative of most fully premixed combustors, indicate that for a sub 5 ppm NO_x performance at full load the primary combustion zone would have to be at an equivalence ratio of less than 0.65. Because of the ability to stabilize the flame at lower equivalence ratios with the LSB, the project team selected a design equivalence ratio of 0.58 which would indicate an expected NO_x performance of about 3 ppm corrected to 15 percent O_2.

To address potential light-off and combustion stability issues in the final combustor design, the combustor was equipped with a pilot gas line which would be able to supply a small quantity of the total fuel and support flame stability with some diffusion burning. However, because diffusion burning would increase NO_x as illustrated in Figure 7, the amount of pilot fuel was limited to a maximum of 5 percent of the total fuel intake at design capacity. Therefore, the function of the pilot fuel was to promote reliable and vibration-free light-off and combustion stability at part load. At full firing rate, the combustor would have to operate without the pilot assistance to achieve lowest NO_x potential. This was only possible if combustion stability was achieved at maximum heat release rate without the pilot. Section 7 describes in greater detail the various stages in the development of the combustor which resulted in final design settings on primary/secondary air split, diameter of the mixing tube, pilot orifice, fuel mixing spokes, fuel intake, and ignitor location.

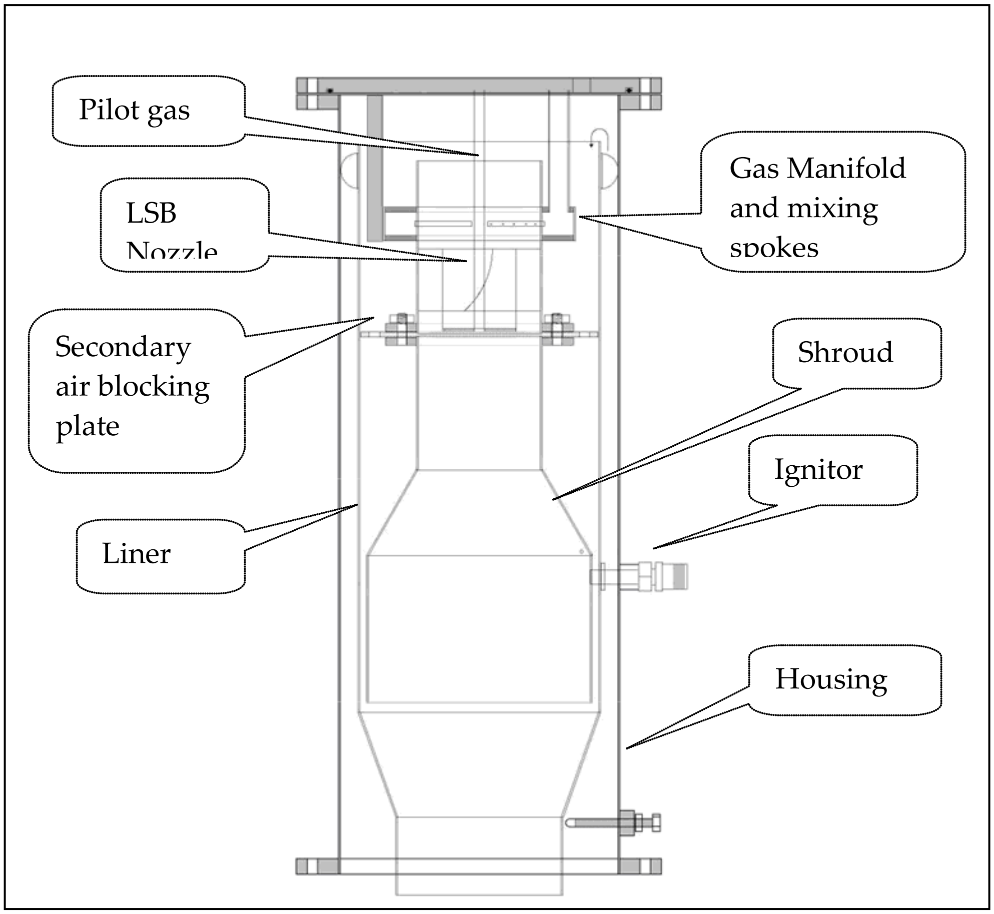


Figure 5: Cross-Section of Silo Combustor Concept Design

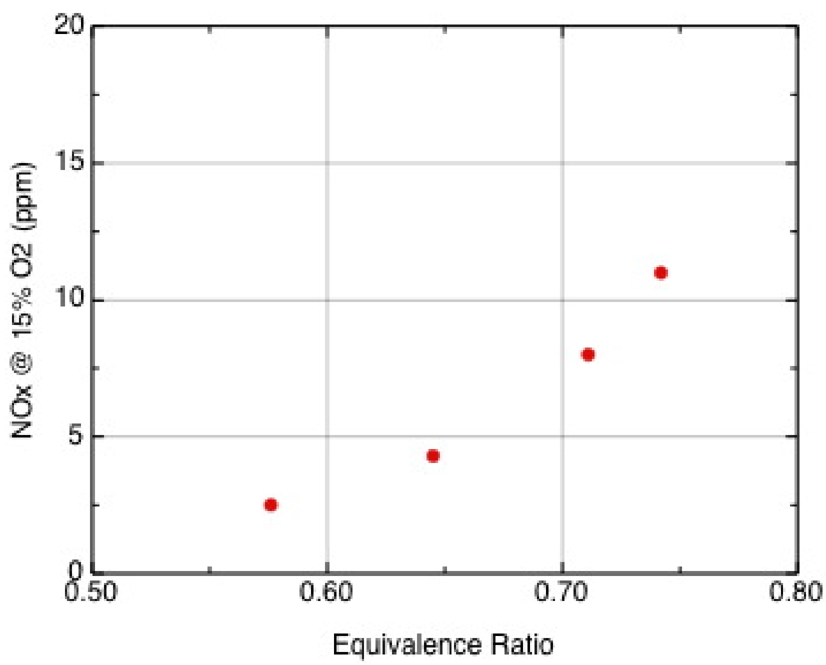


Figure 6: Laboratory Test of NOx Emissions for Final Silo Combustor Design

Figure 8 is a photograph of the components of the first prototype design showing the housing and liner on the left, the mixer, blocking plate and shroud in the middle, and top flange with inlet gas lines and an initial location for the ignitor.

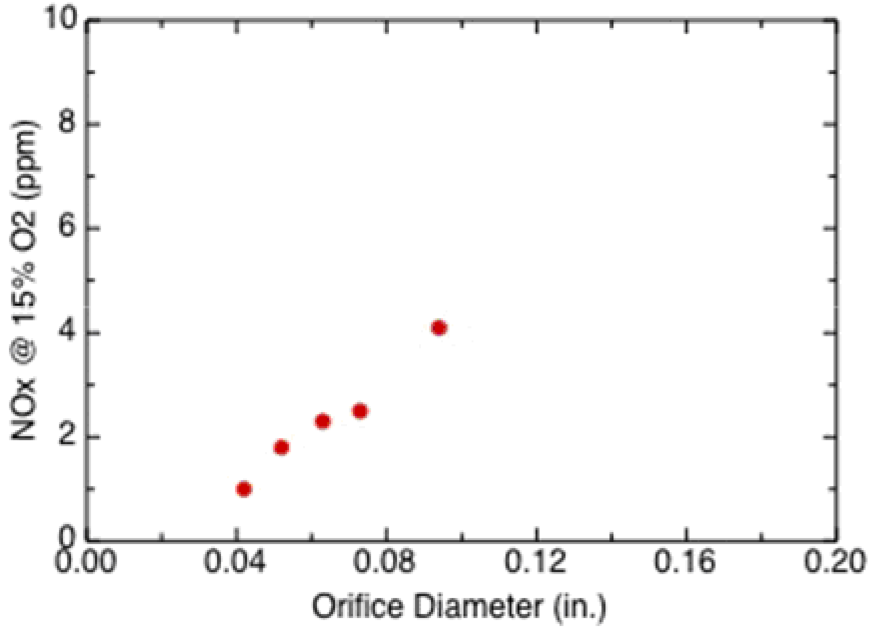


Figure 7: Effect of Pilot Orifice Size on NOx Emissions from the Microturbine

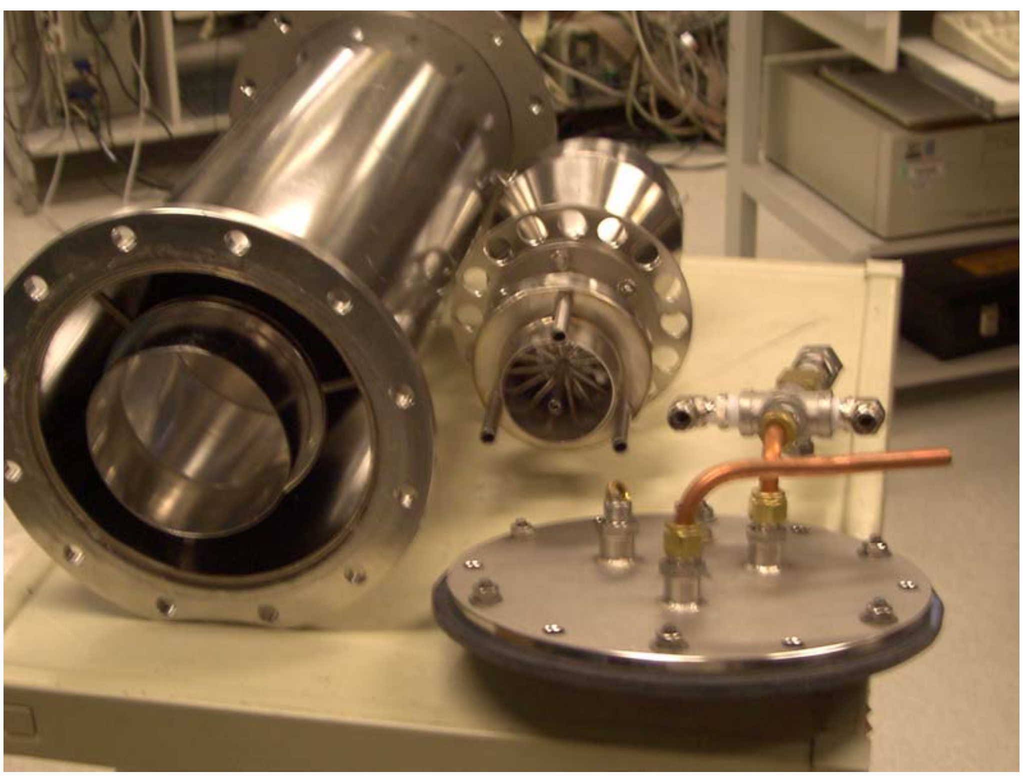


Figure 8; First Prototype Microturbine Combustor Components

Figures 9 and 10 provide greater detail on the LSB nozzle including the swirler vanes and center perforated plate with pilot hole, gas manifold and fuel spokes for maximum mixing efficiency and view from the exit plane of the shroud. Apart for the pilot fuel, the gas is distributed evenly throughout the spinning vanes and center perforated plate.

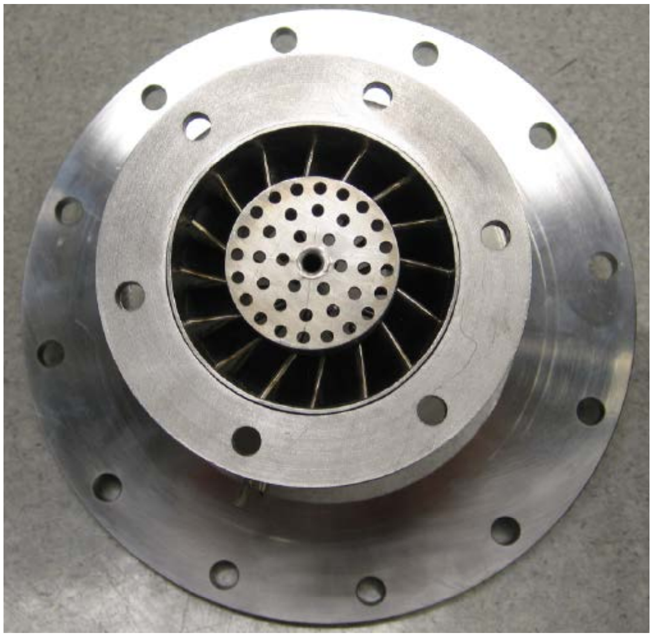


Figure 9: Details of the LSB Nozzle with Perforated Plate and Center Pilot

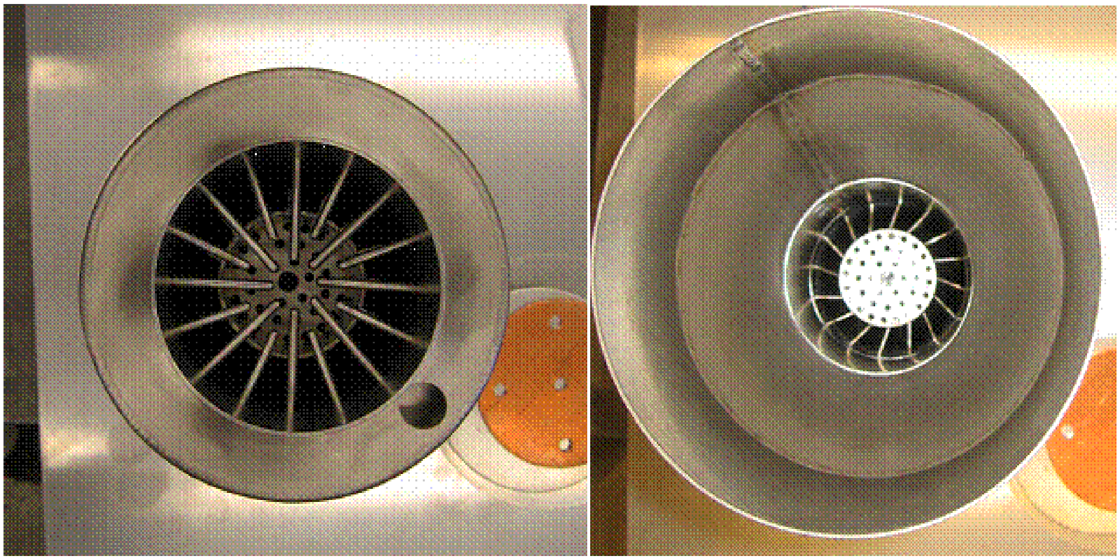


Figure 10: Detail of Fuel Inlet Spokes Inline with Swirler Blades and Burner Exit Shroud

Figure 11 shows a fully assembled combustor with turbine exhaust gas (TEG) exit on the left and fuel intake on the right. The exit plane is contoured to accommodate the engine exit scroll in line with engine rotation. The mounting of the silo combustor on the engine required a new engine housing which was designed and fabricated by CPS and is illustrated in Figure 12

Figure 11; Fully Assembled Silo Combustor

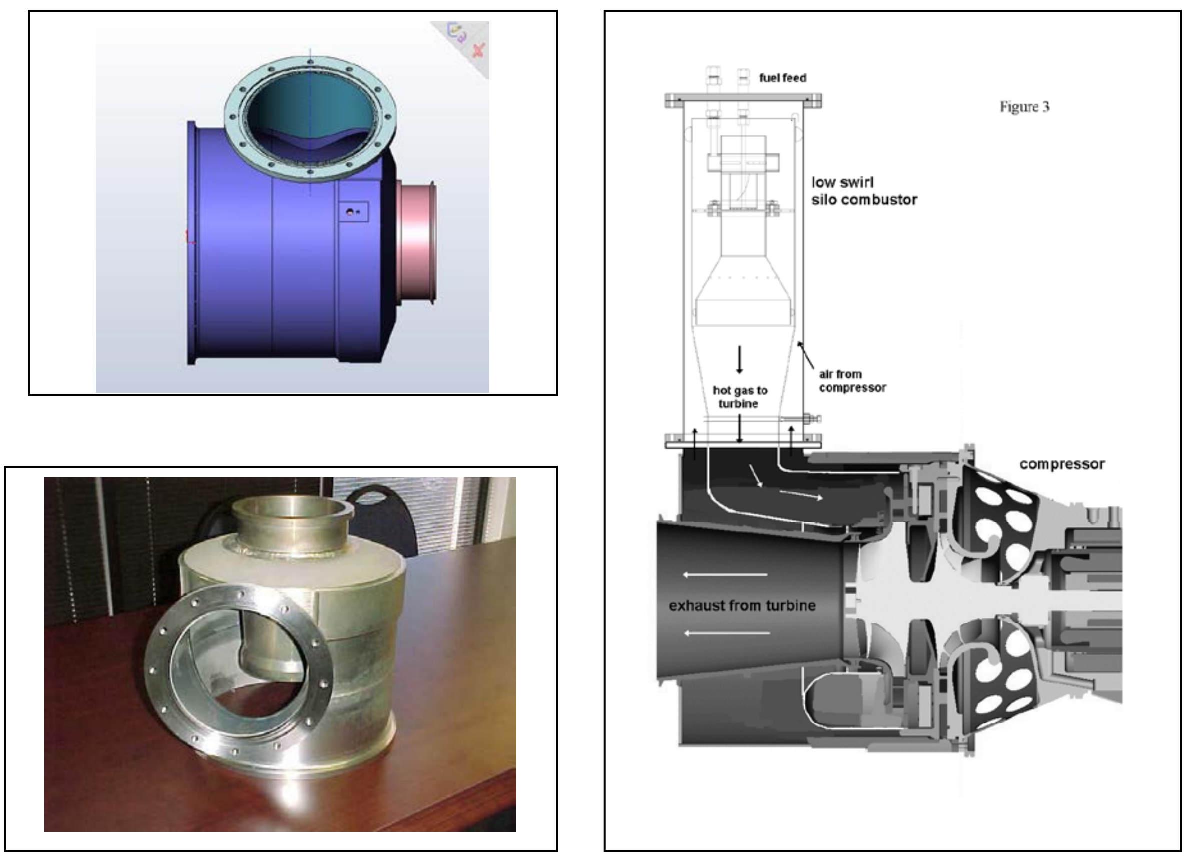


Figure 12: Schematic of Premix Silo Combustor with Microturbine and Fabricated Unit

3.1.3 Performance Testing of Final Design Silo Combustor

Three sets of engine tests with the new combustor were performed at CPS in Stuart, Florida. The first series of tests on the first prototype design showed NO_x levels that were nearly the same as those measured with the conventional fuel staged combustor. These results revealed that the equivalence ratio in the combustion zone was actually 0.78 instead of the targeted 0.58. Furthermore, the thermal paint analyses indicated that the fuel was not sufficiently evenly distributed among the fuel spokes causing some hot spots on the metal surfaces at the exit plane of the flame shroud. Although these temperatures did not exceed metal limits, the design was upgraded to minimize any hot spots. Consequently, design improvements were made to the combustor and a second prototype was fabricated and tested. These results indicated that flame equivalence ratio was much closer to the design point and all hot spots had been corrected with improved fuel distribution and mixing. Final adjustments were made to the combustor including removal of the blocking plate designed to control secondary air bypass as the correct size of primary and secondary air flow areas voided the need for this blocking plate.

Figure 13 shows the test setup in a test cell at CPS in Stuart, FL. The lower portion of the silo combustor is visible fully mounted on the new turbine housing and microturbine. This engine was to eventually be used in the field demonstration.

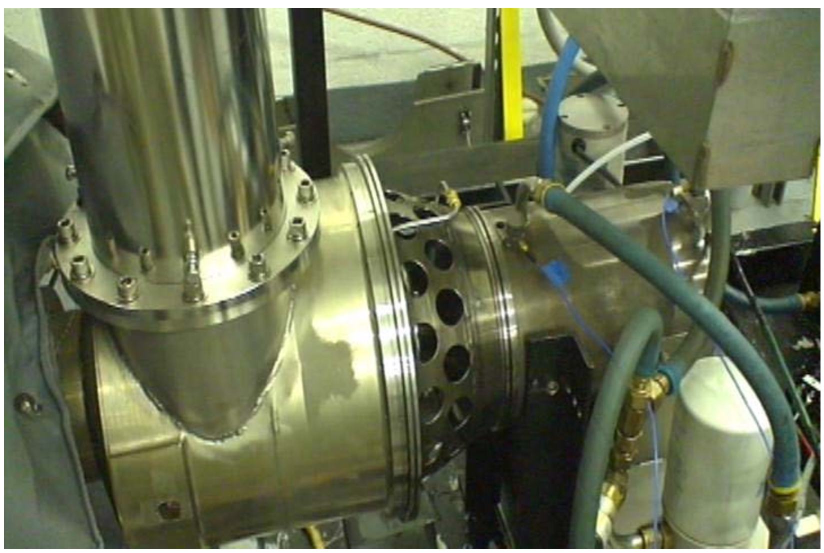


Figure 13: Microturbine Test Cell Setup

Figure 14 illustrates the test results of the final silo combustor design with final adjustments made to the gas openings on the fuel spokes. The engine was tested throughout the load range from 20 to 82.5 kWe. Emissions data are plotted as a function of exhaust gas temperature (EGT) corrected to the International Organization for Standardization (ISO) conditions. When the pilot was set in the "on" position up to 50 kWe for light-off and part load flame stability, NO_x emissions ranged between 7 and 12 ppm, corrected to 15 percent O_2. CO emissions were in excess of 1,000 ppm indicating low adiabatic flame temperature at these lower heat release rates. Above 50 kWe, the pilot was shut off and the flame remained stable. With the pilot in the off position, NO_x emissions ranged between 1.3 and 3.2 ppm, well within the projected target of <5 ppm. CO emissions at full load of about 80 kWe were measured at about 610 ppm. Although too high for an unfired CHP system, these CO emissions do not represent a consideration for the microturbine integrated with the boiler burner because CO will burn out in the boiler when passing TEG through the ULN burner flame. This necessitates a requirement that the boiler burner must be firing when the microturbine is generating power. Under these operating conditions, both NO_x and CO emissions from the microturbine would meet ARB 2007 DG emission requirements and the CHP assembly would also meet local air permit regulations applicable to industrial packaged boilers.

Elliott Energy Systems
Turbo Alternator
ATP EMISSIONS DATA SUMMARY

System Part #:	N/A	System Job #:	J9926
Engine Model #:	TA-80SC-LPM		
Engine S/N:	01-F0020-80	Engine Speed:	68,000
Test Date:	5/16/2007	Combustor Liner P/N:	LEAN PREMIX
Fuel Type:	NG	Combustor Liner S/N:	LEAN PREMIX

	Tested	Goal	Meet Goal?
NOx corrected to 15% O2 at Rated Power - NOX15%R2RAT (PPM)	3.3	9.9	MEET
CO corrected to 15% O2 at Rated Power - CO15%RAT (PPM)	607	41	NOT MEET

Load	Inlet Temp	Ambient Pressure	Relative Humidity	EGT Average	Corrected EGT	O2	NOx	NO	NO2	CO	NOX15%	NOX15%R2	CO15%	Main
KW	°F	PSIA	%	°F	°F	%	PPM	PPM	PPM	PPM	PPM	PPM	PPM	Pilot
0.0	91.6	14.77	55.7	639	553	16.1	5.7	0.8	4.9	1190.0	7.0	7.7	1470.4	Open
20.0	91.6	14.77	55.7	725	631	15.7	9.1	1.5	7.6	1645.0	10.4	11.3	1877.1	Open
49.8	92.3	14.77	50.7	887	779	15.6	10.8	3.9	6.9	1394.0	12.0	12.7	1550.1	Open
59.9	92.7	14.77	50.7	955	841	15.1	1.3	0.6	0.7	1187.0	1.3	1.4	1216.9	Closed
69.9	91.5	14.77	52.8	1014	897	15.0	1.7	0.8	0.8	874.0	1.7	1.8	877.1	Closed
82.5	92.0	14.77	52.2	1089	965	14.8	3.2	1.7	1.4	634.0	3.1	3.3	608.7	Closed

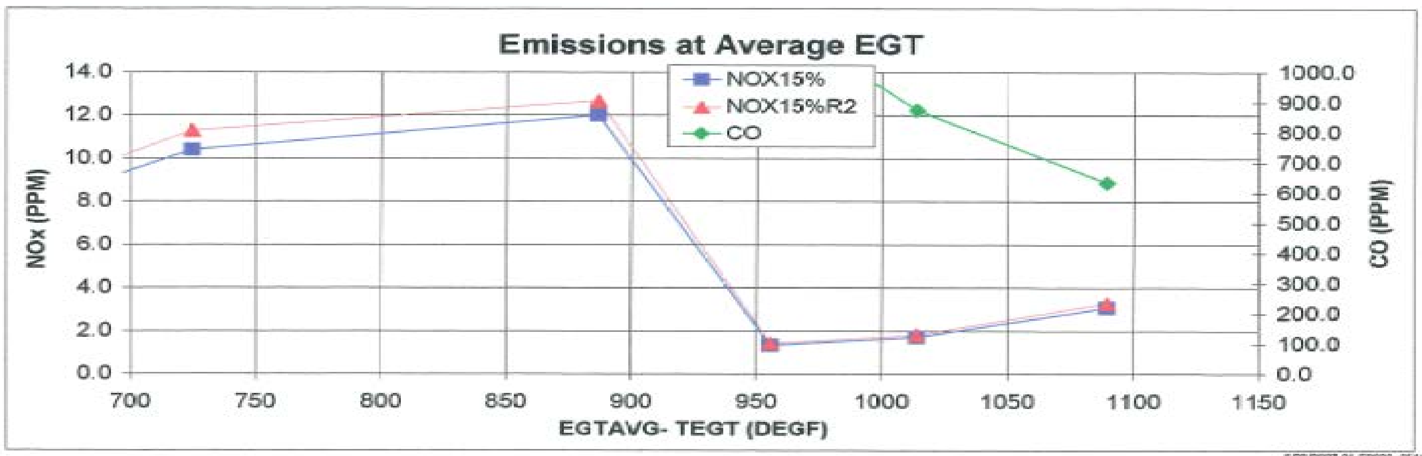


Figure 14: Performance Test Results of Final Silo Combustor Design

3.2 Design and Fabrication of Microturbine-Burner Interface

Concurrently with the development of a low-NO_x silo combustor, the interface between the burner windbox and the microturbine was engineered and designed. The interface design involved several critical decisions on the type of ULN burner, optimum location microturbine location, TEG mixing with ULN combustion air, and effect of microturbine operation on ULN burner. The addition of hot (1,050 to 1,100 F) TEG to the operation of an industrial ULN burner presented some advantages beyond the power generation capability of the MTG. From an energy efficiency viewpoint, the TEG provides and inherent amount of FGR for the ULN burner, as illustrated in Figure 15. For example, the microturbine supplies about 7 percent FGR when coupled with a 30,000 lb steam/hr boiler. In addition to the FGR, the MTG also supplies added combustion air, as illustrated in Figure 16. For example, for the same 80 kWe microturbine and 30,000 lb/hr boiler combination, the TEG supplies nearly 15 percent of the air required by the boiler, more at part boiler load. It is this combination of FGR and added combustion air that significantly reduces the size of the air blower for the ULN burner. This can provide additional incentive for the user to adopt this technology because it will not be necessary to replace an existing air blower for a large one during retrofit of ULN burners and less power is used to supply the same quantity of combustion air and FGR. Also, from a NOx control viewpoint, the hot TEG can provide combustion stability to modern ULN industrial burners improving performance especially at part steam loads. The project evaluated the optimum TEG interface for each Coen ULN type to maximize these advantages.

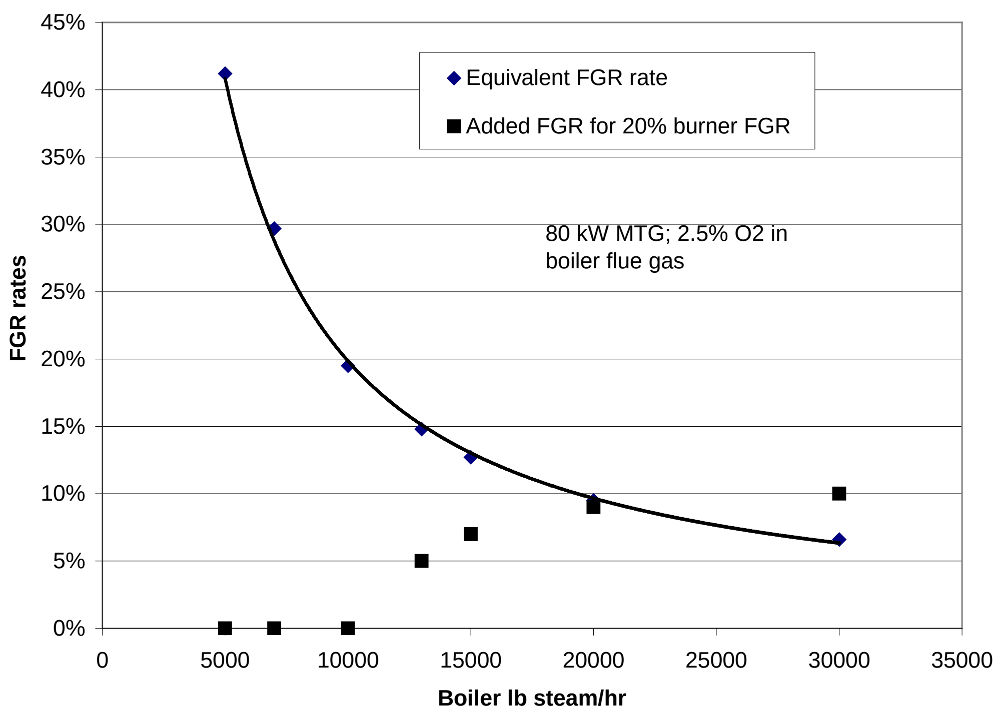


Figure 15: Overall Effect of Microturbine Exhaust on FGR Burner Requirements

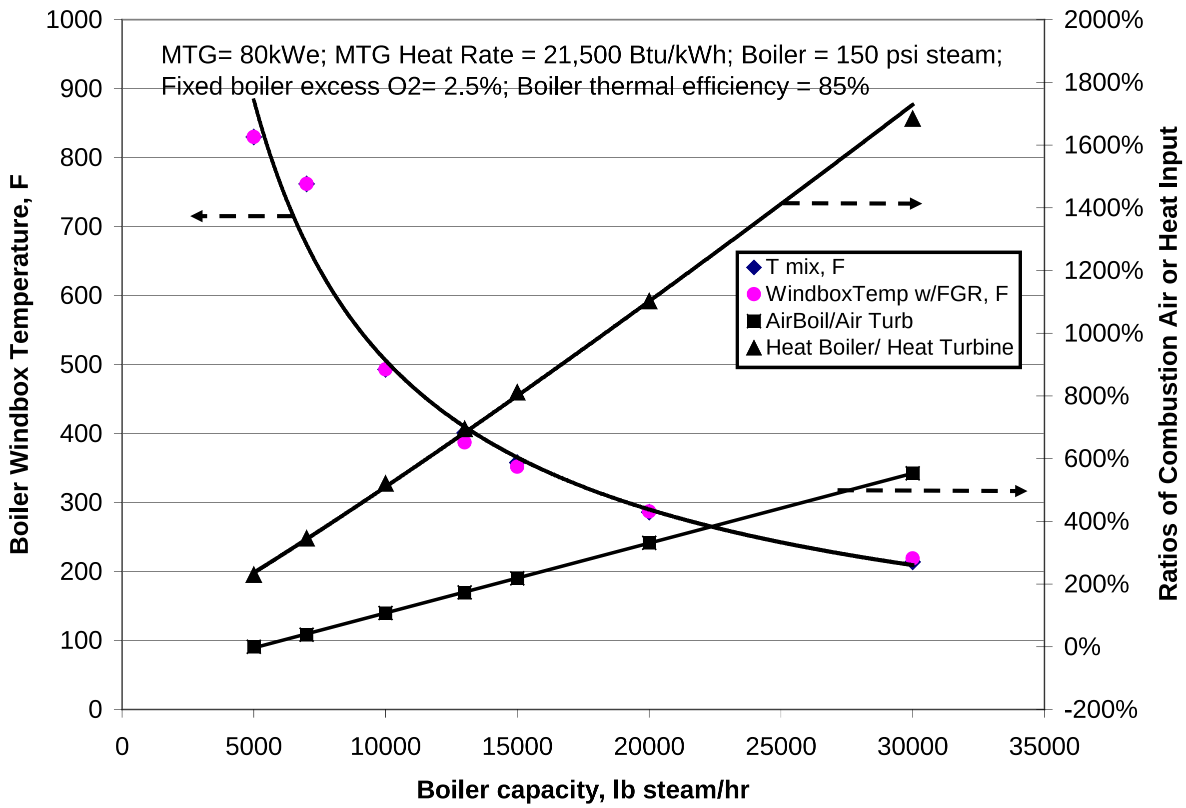


Figure 16: Effect of TEG on Mixing Temperature, and ULN Air Supply

It is also important to note that the microturbine will supply all the combustion air need for boilers with a rated steam capacity of 5,000 lb/hr (about 6 MMBtu/hr). This means that the ULN combustion air blower could be completely replaced by the microturbine, significantly reducing the investment cost for this type of CHP. Furthermore, the microturbine will supply all the FGR necessary for most ULN burner operation, replacing the need for either external or internal FGR.

This section summarizes these developments. Section 7 provides additional detail on each of the tasks associated with this phase of the project.

3.2.1 Coen Burner and Windbox Packages

The project focused on the use of Coen standard Fyr-Compak™ windbox illustrated in Figure 17. This windbox design has been standard with Coen commercial burner sales and therefore it is widely used in industry with currently over 3,000 boiler installations of all four major design types as shown in Figure 17. The design is offered in four typical sizes depending on the firing rate of the burner. Some alterations to this standard windbox design are performed on a site specific basis.

This windbox design provides some attractive features for the CHP integrated package. First, it can be easily retrofit to existing boilers and secondly it provides important cavity space for the integration of the hot sections of the MTG and the mixing the TEG with fresh combustion air from the air blower. The Fyr-Compak™ is used with a variety of Coen-designed burners, each targeted to the primary fuel used by the boiler and the emission regulations applicable to the site.

The project evaluated all of Coen four standard ULN burner types for integration of the TEG and microturbine equipment. The final selection of the demonstration burner awaited the final selection of the demonstration host site and the applicable air permit emission limits. Section 7 provides a description of each of Coen ULN types. For the host demonstration, Coen selected the QLN-ULN™ burner illustrated in Figure 18. The burner requires 20 percent FGR for 15 ppm NO_x capability at full firing rate. Higher FGR rates are necessary for 9-ppm capability. Another important consideration for selecting this burner included the operational capability with preheated combustion air and a maximum pressure drop of 8 inches water gauge (iwg).

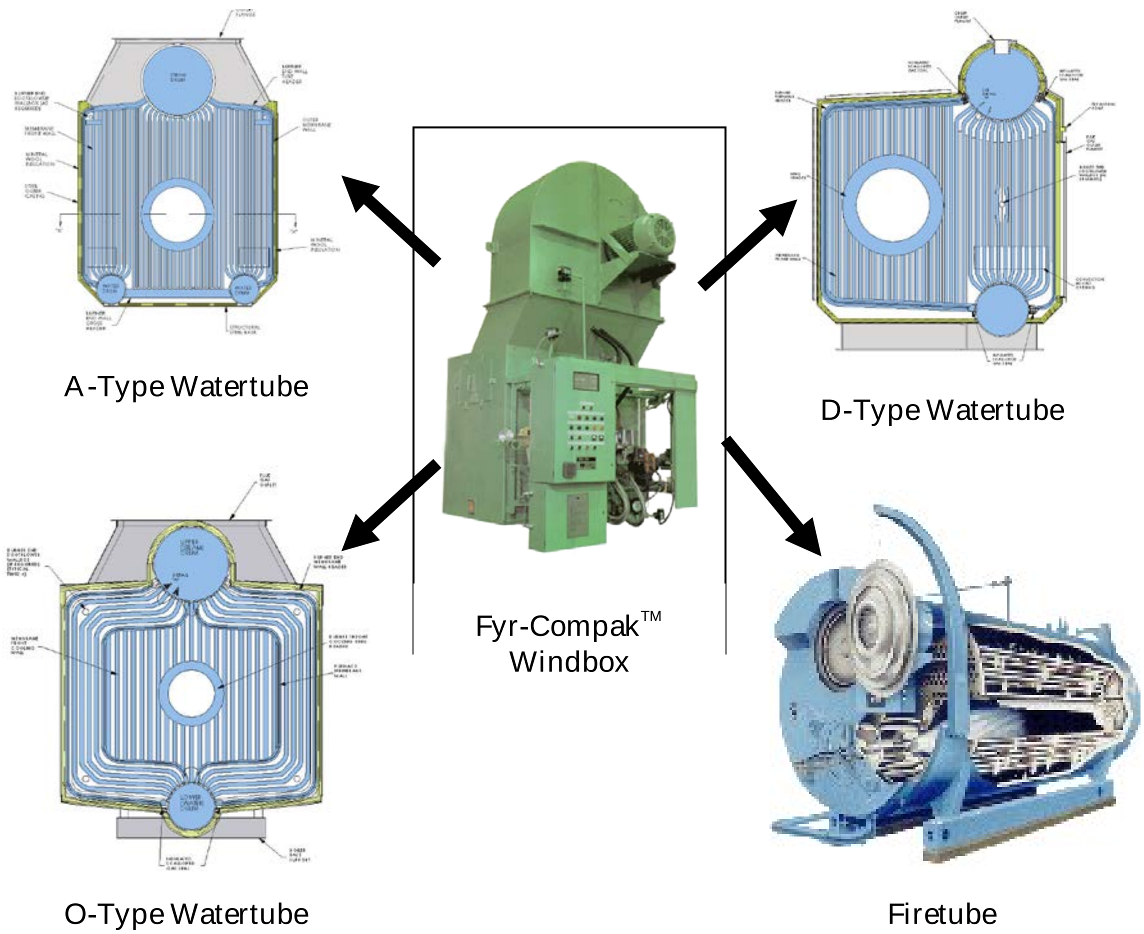


Figure 17: Coen Fyr-Compak™ Windbox and Air Blower Configuration Applicable to All Four Major Packaged Industrial Boilers

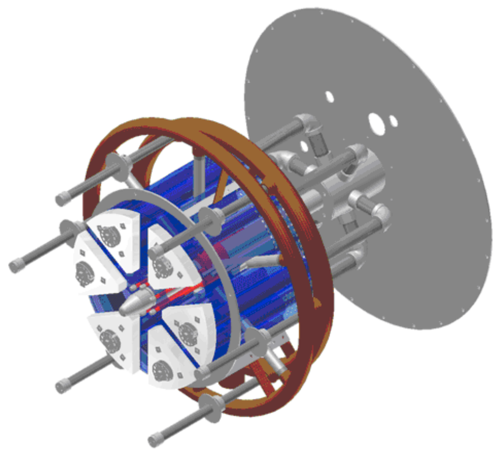
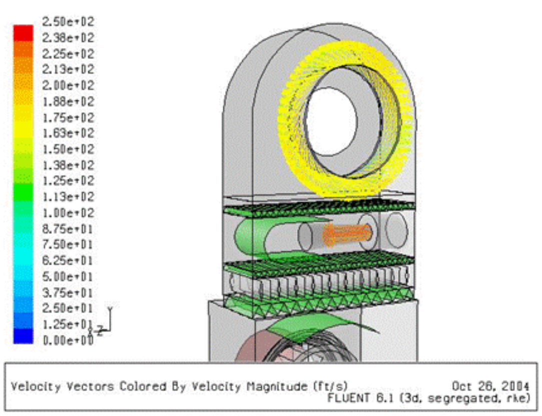


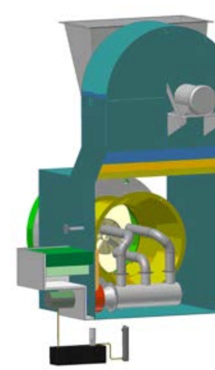
Figure 18: Coen QLN-ULN™ Low NO_x Burner

3.2.2 Evaluation of Windbox and Microturbine Interface Options

Figure 19 illustrates the two options considered in the project for injecting TEG into the boiler burner. Option A considers introduction of the TEG directly at the discharge of the combustion air blower. The microturbine compressor inlet is placed on the outside to be able to supply additional combustion air and thus reduce load on the ULN blower. After detailed CFD analysis, it was decided that this option did not produce the desirable uniformity of TEG exhaust at the burner exit. In addition, windbox temperatures would be excessive in some retrofit cases for smaller boilers, as illustrated in Figure 16. Efforts to improve mixing increased back pressure at the detriment of the energy saved. Therefore, the selected interface design hinged on introducing the microturbine exhaust directly in the windbox and distributing it using a mixer (bustle) that provided directional use of the hot vitiated air from the microturbine to assist in ULN burner operation.



(a) Air Blower Outlet Location



(b) Windbox Location with Burner Distribution Bustle

Figure 19: Interface Configurations Explored for Location of Microturbine Exhaust Inlet

The following section summarizes the result of the CFD modeling of the windbox interface configuration utilizing a mixing bustle.

3.2.3 Air Flow Modeling

A series of CFD modeling analyses were then undertaken to evaluate the efficacy of a distribution bustle in providing uniform mixing of TEG with incoming FGR-diluted air from the combustion air blower. Optimum distribution of the hot microturbine TEG is important in maintaining the design operating specifications for the ULN burner with variable steam load on the boiler. Two different bustle designs were evaluated. This section highlights the predicted performance of the selected design. Additional detail on both bustle designs can be found in Section 7. Figures 20 and 21 illustrate the boundary conditions selected for an 80 kWe simple cycle microturbine and a combustion air blower supporting the operation of a 30 MMBtu/hr boiler. The blower inlet temperature is higher than ambient because of the mixing of external 400° F FGR with ambient air required for NOx emission control.

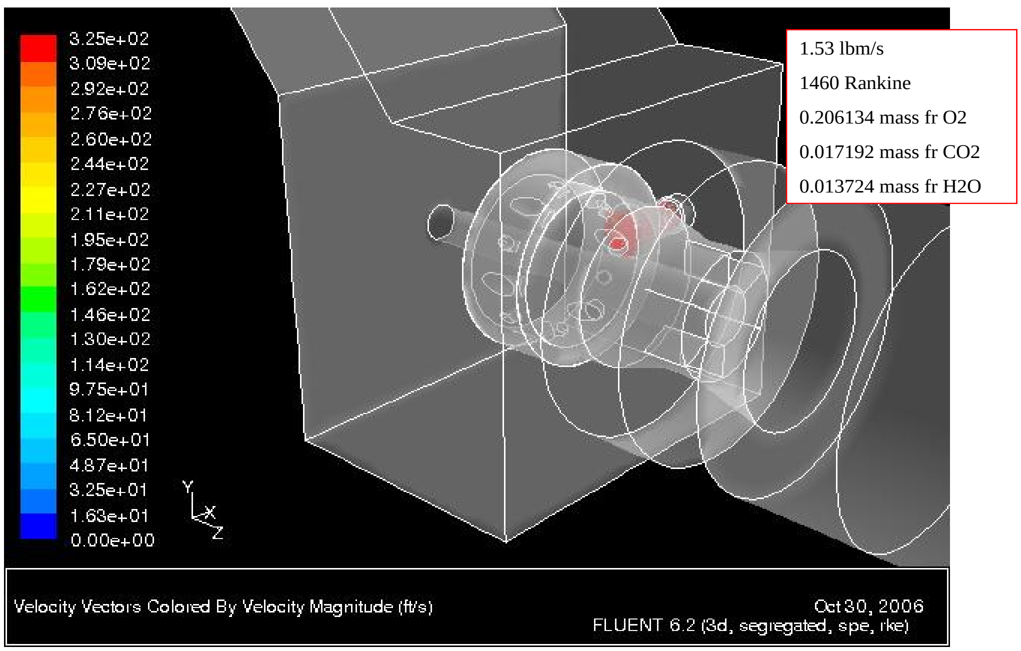


Figure 20: Microturbine Conditions at Inlet to Mixing Bustle

Figures 22 and 23 illustrate the temperature and the excess oxygen profile of the mixed gas achieved with one of two mixer bustle designs considered in the CFD analysis. Details of the bustle designs are given in Section 7. For the most part, predicted variations in temperature, flows, and oxygen partial pressure were considered acceptable and well within burner tolerances for optimum NOx performance and turndown.

Table 3 lists the calculated pressure drops. For the bustle design selected for manufacturing, the microturbine exhaust will see a back pressure of 5.45 iwg. With a boiler furnace pressure of 4.22 iwg, the pressure drop due to the insertion of the mixing bustle is about 1.23 iwg. This back pressure and pressure drop will not affect the generation capacity of the microturbine significantly. If the back pressure was considered excessive, the project team also evaluated placing the microturbine compressor within the Fyr-Compak™ windbox.

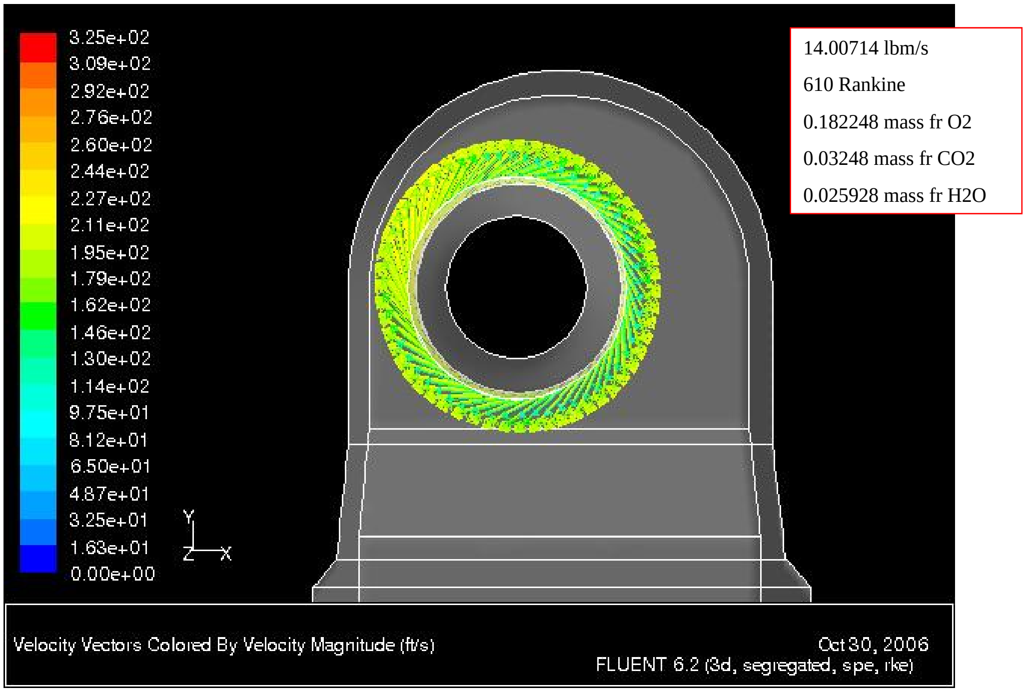


Figure 21: Combustion Air Blower Conditions

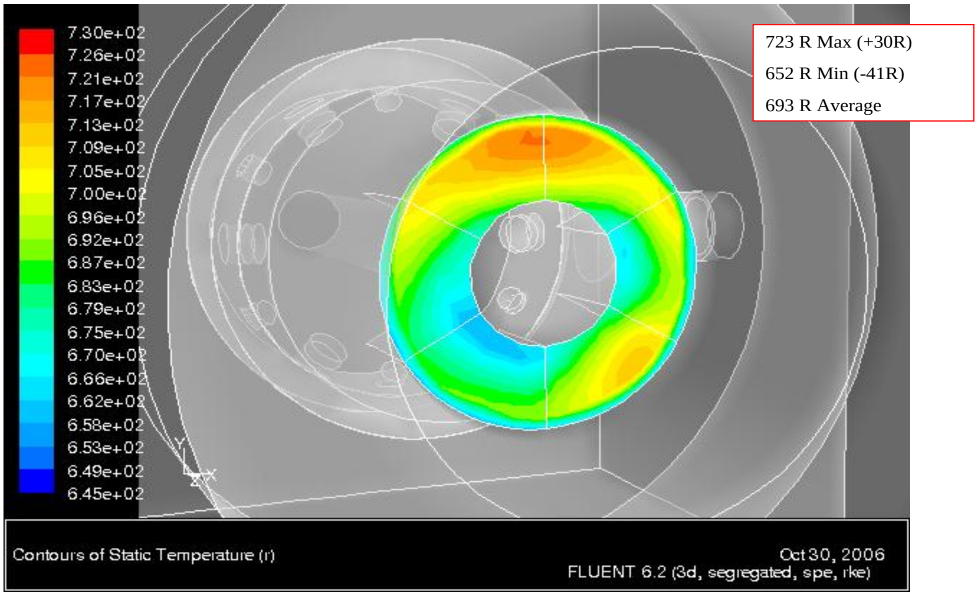


Figure 22: Temperature Distribution of Vitiated Combustion Air at Burner Exit - 100% Load

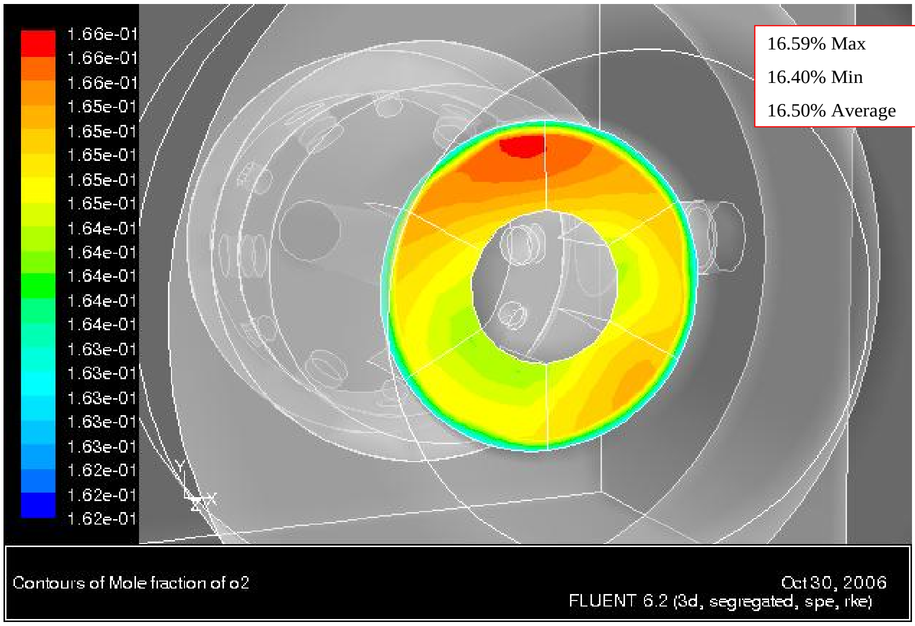


Figure 23: Excess Oxygen Concentration of Vitiated Combustion Air at Burner Exit - 100% Load

Table 3: Pressure Drop Calculations for Turbine Exhaust with Bustle

Parameter	Mixer A	Mixer B
Windbox Inlet Static Pressure (iwg)	5.42	5.32
TEG Plenum Inlet Static Pressure (iwg)	4.58	4.23
TEG/Bulk Downstream Static Pressure (iwg)	3.15	2.94
TEG Plenum Static Pressure Drop (iwg)	1.43	1.29
Turbine Exhaust Total Pressure (iwg)	5.86	5.45
TEG/Bulk Downstream Total Pressure (iwg)	4.42	4.22
TEG Plenum Total Pressure Drop (iwg)	1.45	1.23

3.2.4 Heat Transfer and Acoustic Considerations

The windbox of ULN burners is typically at temperatures higher than ambient due to the external 400 F FGR used in NO_x control. In most design, this FGR is taken from the boiler stack and ducted to the inlet of the combustion air blower. For this type of FGR installation, the capacity of the air blower is reduced accordingly. Convective heat losses are minimal as the bulk mixing temperature of the vitiated air in the windbox is typically below 140° F. Excessive FGR rates will eventually require windbox insulation for some installations.

The addition of a TEG mixing bustle with inlet temperatures of 1,050° F is bound to raise the windbox temperature. This temperature rise is due to the blower air which provides constant forced convection cooling of the bustle with eventual heat recovery in the boiler. A heat transfer analysis was performed for a simple cycle 80 kWe microturbine integrated with a 45 MMBtu/hr burner windbox. The results showed that at full load, the inside windbox temperature would increase by 60° F rising the overall bulk windbox temperature to 212° F with 30 percent FGR. With a 0.5 inch thick insulation the incremental heat loss from the windbox due to TEG on the order of 0.005 MMBtu/hr or about 0.25 percent of the heat input from the microturbine. The overall effect on the boiler efficiency would be a minimal reduction of 0.004 percent.

In addition, an evaluation of the noise effect of adding a microturbine to a boiler was undertaken. The noise and heat transfer analyses are presented in more detail in Section 7.5. However, the conclusion on the noise consideration would indicate that current noise from existing combustion air blower have an average dBA of 82.5, whereas the microturbine has a cabinet-enclosed microturbine has a noise level of 67-75 dBA and the gas compressor produces a noise level of 68-71. Therefore, no additional noise suppression was considered necessary beyond the requirement to house the combustion air inlet side of the microturbine in its own enclosure.

3.2.5 CHP Prototype Integration Design

The objectives of the CHP design for the simple cycle microturbine integrated with the burner windbox were to develop an assembly that required least foot print; provided for ease of all waste heat recovery from the microturbine; and consisted of a simple low-cost design with ease of access for maintenance and operation.

Figures 24 and 25 illustrate the front and side views of the prototype package for the integrated microturbine-burner CHP. The key design features of this assembly are the exposure of the hot side of the microturbine to the forced convection cooling within the windbox. Therefore, the silo combustor and the microturbine are cooled by the ULN burner combustion air. The cold-end section of the microturbine is separated from the hot side by a plate which isolates the fresh air intake side from the hot section. This section of the microturbine requires sound insulation consistent with conventional microturbine packages. To prevent low heat accumulation in the cold section due to the generator and oil cooling loop the CHP assembly design also required some cooling of the generator oil via a heat exchanger. This low-temperature heat is also recovered by the system as it is dissipated into the cold intake of the microturbine.

The ULN burner is equipped with the bustle that distributes the hot microturbine exhaust strategically around the burner where high-temperature vitiated air can provide added burner performance in controlling NO_x and achieving combustion stability at full and part boiler loads. This version of the ULN burner assembly does not have backup distillate oil firing capability. Depending on host site requirements, final CHP assembly design must consider fuel burning requirements and local air permit levels. These issues were addressed after the selection and final retrofit agreements drafted between the project and the selected host facility. Therefore, some additional features of the ULN and actual location of the bustle were finalized after these initial prototype designs were developed.

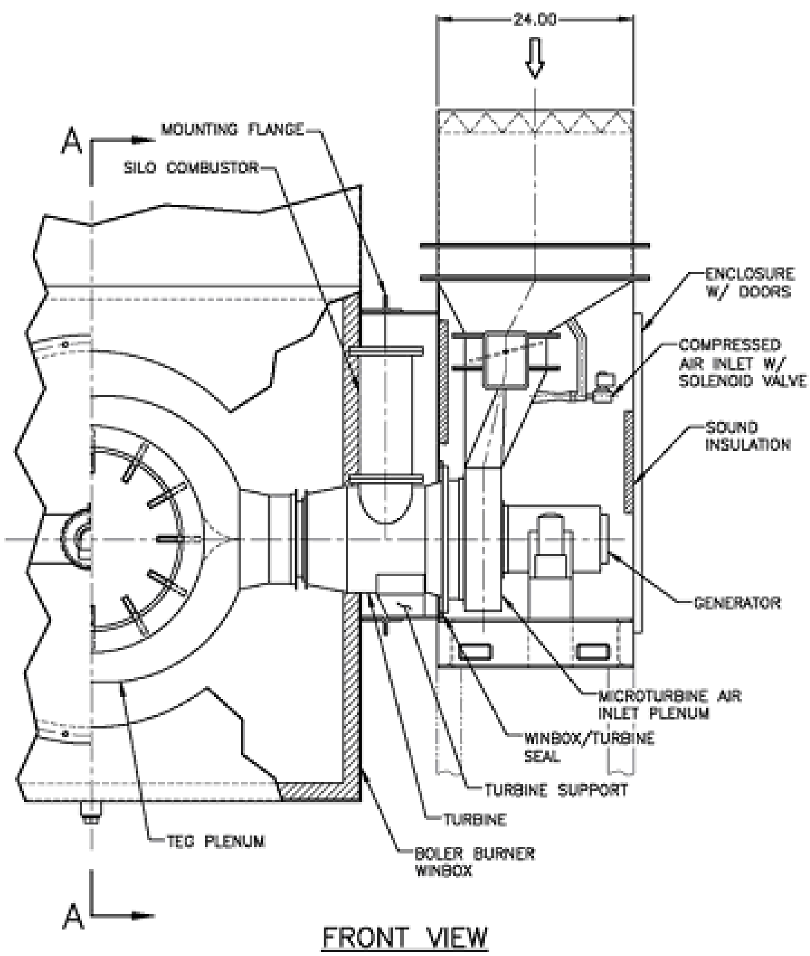


Figure 24: Prototype Design of Microturbine Interfaced with Burner Windbox and Burner – Front View

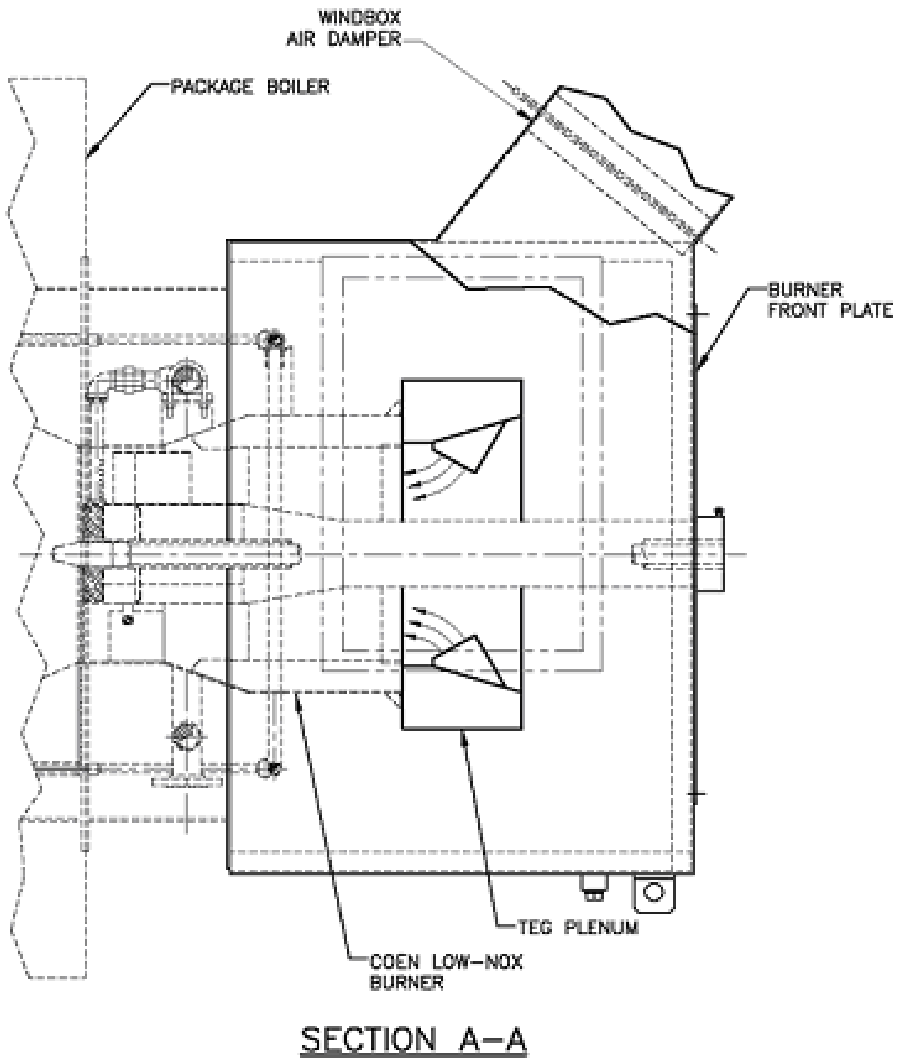


Figure 25: Prototype Design of Microturbine Interfaced with Burner Windbox and Burner - Side View

3.3 Integrated CHP System Assembly

To support the development of the integrated CHP design and validate the acceptable performance of the Coen ULN burner and necessary windbox modifications, this phase of the project included a series of tests performed at Coen's research test yard. One these tests provided confirmation of the selected system integration approach described in Section 3.2, the project could proceed with the final integration and microturbine enclosure designs and subsequent fabrication. This section summarizes the work performed in this portion of phase 3.

3.3.1 Testing of a Prototype CHP System

A series of tests were performed at the Coen Test Yard in Burlingame to document the operation of a Coen ULN with the exhaust from the unrecuperated 80 kWe microturbine. For these prototype CHP tests, Coen utilized 40 MMBtu/hr Delta NOx™ and the unmodified microturbine equipped with the original CPS partial oxidation combustor, as the silo prototype was undergoing final development testing in Florida. These tests also served to validate the operational status of the microturbine equipment and to identify any component upgrades necessary for the final design. Figures 26 and 27 illustrate the test setup. The simple cycle microturbine was left in the original package as the objectives focused principally on the impact of the exhaust on the burner stability, FGR requirements, and incremental emissions measured at the boiler stack.

Figure 26: Test Yard Setup Used in Prototype CHP Configuration

Figure 27: Simple Cycle CHP Test Setup

The hot exhaust from the microturbine was ducted to the side of the Fyr-Compak™ windbox and channeled to the burner with a prototype design of the bustle shown in Figures 28 and 29. The manifold was used to provide adequate distribution of the hot vitiated air around the burner throat, a requirement specified by Coen. This feature was adopted for the final integrated CHP design, as discussed in Section 3.2. An additional duct was used to connect the windbox to the microturbine air intake filter. This was deemed necessary to prevent backflow of ULN induced FGR through the microturbine. When the microturbine was firing a damper closed this flow. However, some vitiated windbox air was likely being introduced to the microturbine inlet air because the windbox was pressurized and the damper was not likely to be completely sealed. This may have introduced some FGR from the boiler to the microturbine air intake with some interesting results indicated below.

Figure 28: View of Preliminary Bustle and Windbox TEG Inlet Flange

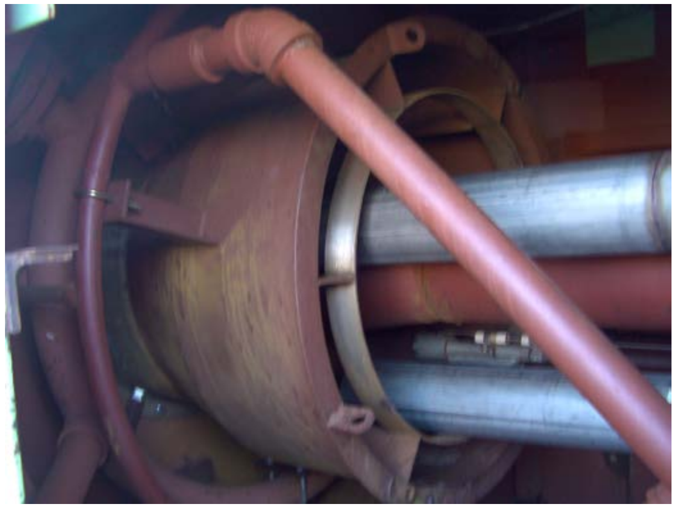


Figure 29: View of the ULN Burner Inlet with Microturbine Exhaust Gas Piping

Microturbine emissions during these prototype CHP tests are reported in Table 4. Microturbine emissions were measured in the connecting duct to the windbox, indicated NO_x levels at 80 kWe in the range of 9 to 18 ppm as measured at 16.1 to 16.6 percent excess O_2 dry basis. The boiler ULN was not firing during Tests 5, 6, and 7. NO_x emissions were higher when the boiler burner was not firing, i.e., 16-18 ppm versus 9-12 ppm. This result is attributed to the likely effect of the FGR from the windbox which diluted the oxygen concentration in the microturbine air intake. This in an interesting result as it might apply to the future integration of the microturbine air intake within the windbox. CO emissions measured from the microturbine were in line with those of the uncontrolled CPS engine, ranging from about 220 to 370 ppm. CO emissions from the microturbine will not represent a concern because CO will be fully oxidized within the ULN flame. The exhaust from the microturbine at full 80-kWe capacity was measured to have a temperature in the range of about 993 to 1,044° F. The microturbine was not operating during Test 11.

Table 5 summarizes the boiler burner emissions data with coupled microturbine operation. As shown, the NOx emissions from the boiler are affected by firing rate and level of FGR induced by the combustion air blower to the burner windbox. At near maximum firing rate for the Delta NOx™ of 37.7 MMBtu/hr (Test 10), total NO_x emissions from both the burner and microturbine were measured to be 18.2 ppm corrected to 3 percent O_2 with an induced FGR rate of about 30 percent. These test results indicated that the microturbine NO_x levels do not add significantly to the overall boiler emissions and compliance with local permit levels in the range of 9-15 ppm, corrected to 15 percent O_2 with FGR rates of about 37 percent.

When comparing the NO_x results between Tests 8 (with microturbine) and 11 (without microturbine), the uncontrolled microturbine indicates a total contribution of about 7 ppm to the boiler stack when the boiler is firing at about 19 MMBtu/hr. With a low NO_x microturbine, emitting less than 5 ppm NO_x and a ULN FGR rate of 30 percent, total CHP emissions would be well below 15 ppm at full load required to meet current NO_x regulations in California affecting industrial packaged boilers. With the boiler operating at about 11.7 to 13.8 MMBtu/hr (or 5 to 8 times the heat input to the microturbine), NO_x emissions from the combined system were 29 to 33 ppm corrected to 3 percent O_2, indicative of higher microturbine NO_x contribution at low firing rates. Also, the tests indicated that the operation of the burner was deemed satisfactory as combustion remained stable and turndown was not affected. Another important result relates to the burnout of microturbine CO emissions. This is evident by the very low CO concentrations measured at the boiler stack.

3.3.2 Design and Fabrication of Microturbine Enclosure Package

With completion of the microturbine low NO_x modification and selection of the prototype design for the integration of the microturbine with the ULN burner and windbox assembly, work moved toward completion of the final microturbine enclosure package and final CHP system configuration. Figure 30 shows the final design of the microturbine enclosure and Figure 31 are photographs of the hot and cold sides of the fabricated microturbine enclosure.

Table 4: Microturbine Emissions during Prototype Testing

Test No	MTG kW	MTG RPM	EGT °F	Ambient Temperature °F	Excess O_2, %	NO_x As measured	CO As measured
5	70	68000	950	73	16.6	16	257
6	80	68000	1024	77	16.1	16	259
7	80	68000	1038		16.1	16	241
8	80	68000	1031		16.2	16	220
9	80	68000	1044		16.1	18	221
10	80	68000	1044		18.5	18	226
11	0						
12	5	68000	635	70	18.5	6	19
13	80	68000	993		16.3	12	220
14	80	68000	1008		16.3	12	325
15	80	68000	1000		16.3	9	370
16	80	68000	1000		16.3	15	235

Table 5: Emission Performance of ULN Burner without Microturbine

Test No.	ULN Firing Rate MMBtu/hr	Induced FGR %	Stack O_2, %	Stack NO_x ppm@3%O_2	Stack CO ppm@3% O_2
8	18.8	29.9	3.3	18.3	0
9	24.5	30.2	3.3	19.3	0
10	37.7	30.3	3.2	18.2	0
11	18.9	28.0	3.7	11.4	29
12	18.9	33.0	5.8	24.8	8
13	18.9	34.3	4.3	24.8	4
14	13.8	31.4	3.8	29.3	4
15	11.7	45.6	3.6	32.0	2
16	11.7	44.6	4.3	33.4	2

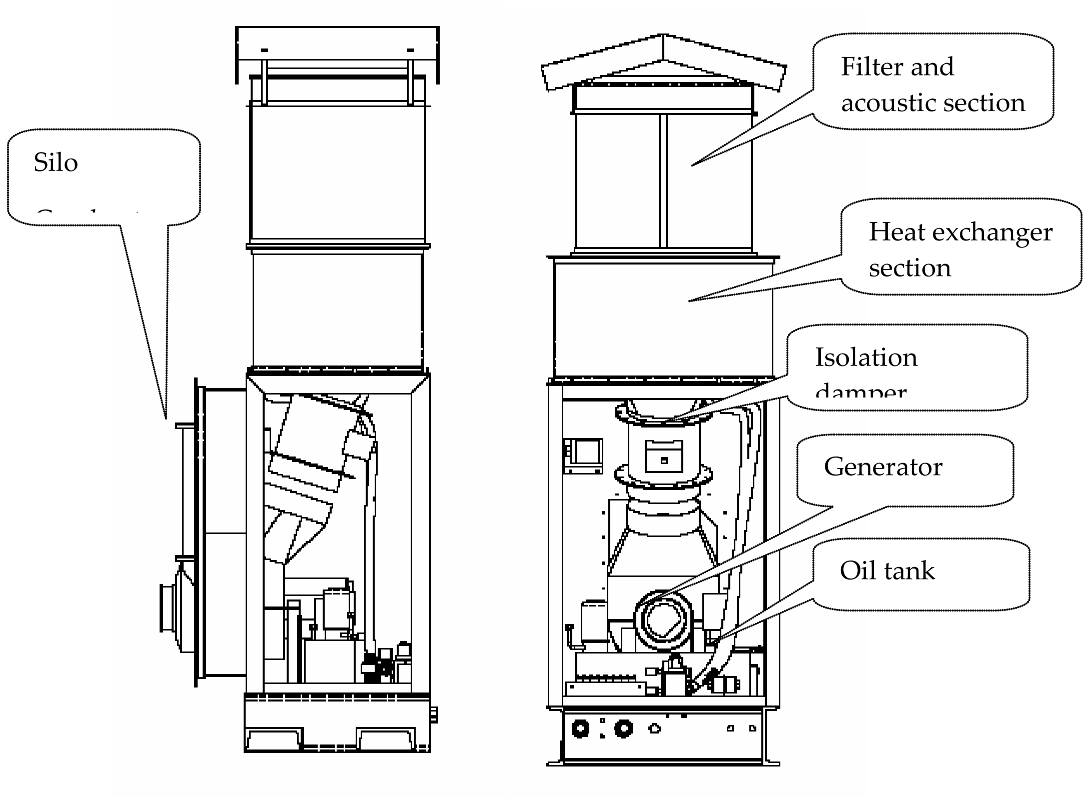


Figure 30: Front and Side Views of Microturbine Enclosure

Additional modifications to the final design and included in the fabrication involved the use of a microturbine isolation valve and actuator and the insertion of the oil cooler heat exchanger in the air intake of the microturbine for total heat recovery. The isolation valve was deemed necessary to isolate the microturbine and prevent windbox air to pass through the microturbine and vent into the ambient air. This will also allow the boiler to operate independently of the microturbine during routine maintenance and repairs. The orange colored actuator and valve assembly are visible at the top of the air intake. On the hot-side of the enclosure, the two fuel lines for the combustor, one for the diffusion pilot and one for the premixed fuel are clearly visible. Also shown is the ignitor wire which penetrates the housing, the liner and the diverging burner shroud.

3.3.3 Integrated CHP Assembly

Figure 32 illustrates the overall CHP assembly. The orange-colored equipment points to the equipment added to a conventional industrial packaged boiler. This includes the microturbine enclosure, the gas compressor and power electronics (PE) cabinet. The microturbine enclosure is fully integrated with the burner and windbox and occupies the least footprint in this adopted configuration. The gas compressor and PE unit can be located away from the microturbine in areas that do not have sufficiently available floor space next to the boiler.


Figure 31: Views of the microturbine cabinet – Left: Cold Side; Right: Hot Side

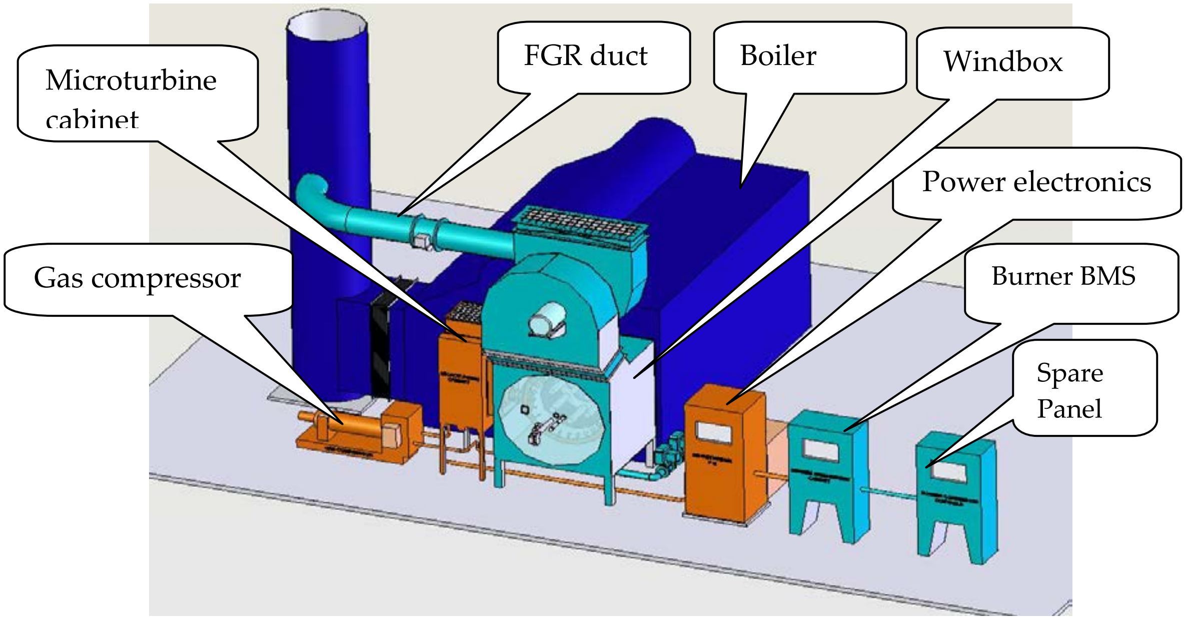


Figure 32: CHP Equipment Arrangement

The arrangement illustrates that the PE unit is located next to the burner BMS and power service panel to provide required interface with the burner and supply electricity to the plant.

3.4 Field Installation and Demonstration Testing

This section highlights the work performed in securing the host site and completing all the design engineering and fabrication of the CHP assembly as well as the results of the field demonstration testing. The work addresses the scope included in Tasks 15 through 18 of the project.

3.4.1 Host Site Selection Process

In California, industrial packaged (single burner) boilers with heat input capacities of 10 MMBtu/hr and above are entirely natural gas fired and are strictly regulated by local air districts. These regulations impose NO_x limits that vary between districts and can be as low as 9 ppm for more modern installations to as high as 30 ppm @ 3 percent O_2 for older ones. Some districts are currently considering retrofit rules to limit NOx to levels as low as 5 ppm @ 3 percent O_2 for existing base loaded units. Therefore, the selection process for the demonstration of this CHP technology focused on the following criteria:

1. Host site with spare boiler steam capacity to permit the retrofit of one unit without interfering with steam supply during shutdown for scheduled retrofit;
2. Boilers in the size range of 20 to 60 MMBtu/hr heat input capacity to minimize the retrofit cost of burner hardware and demonstrate capability to operate entirely off the power grid;
3. Boilers with a currently high NO_x emissions to provide additional incentives to the host facility beyond those of cost-effective self-generation and electricity savings;

4. Boilers with a swing-load steam demand to permit measurement of CHP performance at all boiler load and test ULN capability at part load with microturbine firing;
5. Boilers with existing FGR capability to minimize retrofit cost;
6. Boilers with sufficient combustion air blower capacity to provide operational flexibility and reduced power consumption with microturbine supplied air;
7. Plants with management awareness of environmental and energy efficiency stewardship, including reducing carbon footprint.

As the firing capacity of the boiler increases compared to that of the microturbine, the overall CHP efficiency increases asymptotically to the overall efficiency of the boiler as illustrated in Figure 33. The power conversion efficiency of the microturbine is nearly perfect and only diminishes with the latent heat of vaporization of the moisture in the TEG and energy losses associated with power to operate gas compressor and power electronics auxiliary equipment.

3.4.2 Host Site Description

The project selected the Hitachi Global Storage Technologies (GST) plant is San Jose, California for its field demonstration of the integrated CHP system that combines a simple cycle microturbine with an industrial boiler low-NO_x burner. The Hitachi plant operates six boilers at their steam plant used to provide district heat for all the buildings at the site. The site requires a maximum of three boilers operating full time to supply district heating according to seasonal requirements.

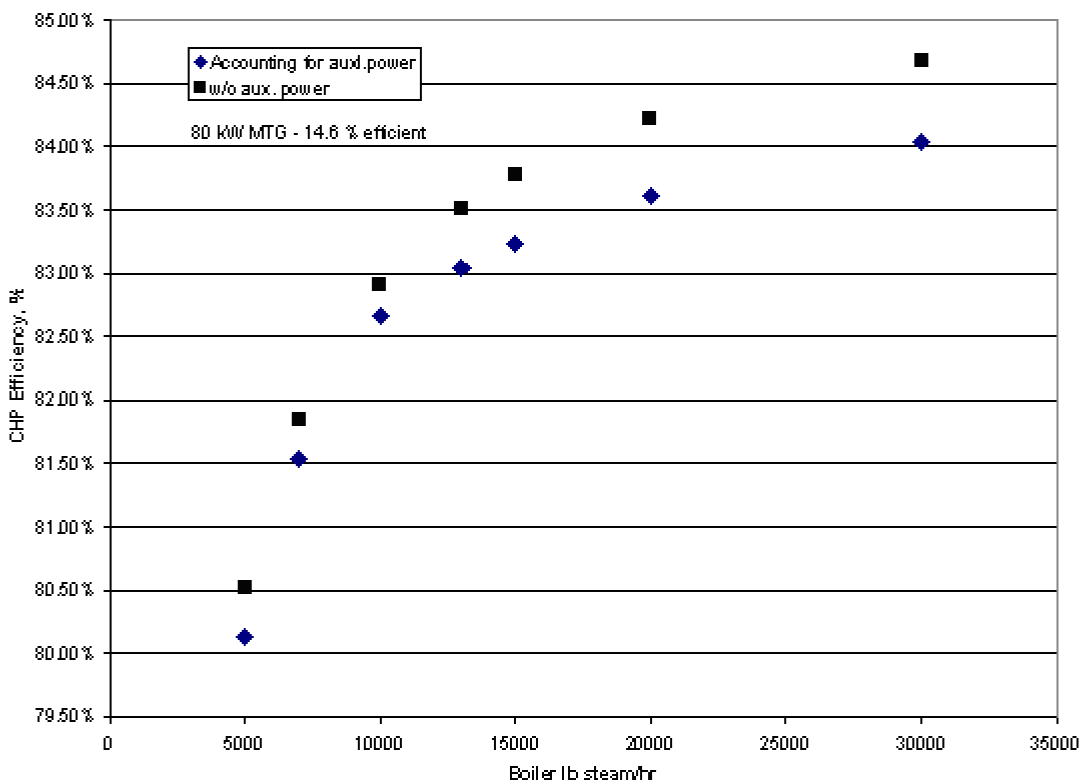


Figure 33: CHP Efficiency with Boiler Capacity for Simple Cycle 80 kWe Microturbine

The plant selected Unit 3 for the retrofit demonstration. This packaged Cleaver Brooks Model D-60 watertube boiler has a nameplate steam capacity of 32,000 lb/hr at a pressure of 260 psig, corresponding to a heat input of about 36 MMBtu/hr at full load. Figure 34 illustrates the front and side views of a typical packaged, single burner, D-type watertube boiler. Prior to CHP retrofit, the boiler was derated to 28,000 lb/hr in order to meet the Bay Area Air Quality Management District (BAAQMD) NO_x rule of 30 ppm at 3 percent O_2. The pre-retrofit burner utilized an early vintage Coen low-NO_x burner with an external FGR duct, illustrated in Figures 35 and 36. The low-NO_x operation used a separate FGR fan with the duct connecting directly to the side of the windbox as shown in Figures 37. The burner was also capable of firing with distillate fuel during natural gas curtailments.

The BAAQMD issued an operating permit for the retrofit of the CHP system for Unit 3 based on limiting total NO_x and CO emissions to 15 ppm and 50 ppm at 3 percent O_2 respectively with both microturbine and boiler firing at full capacity. Therefore, Coen Company selected the retrofit of a modern dual-fueled QLN™ which is designed to reach 15-ppmNO_x with and FGR rate of about 10-25 percent (about 5-20 percent premixed and another 5 percent selective). The premixed FGR will be introduced via the external FGR duct, whereas the selective FGR would be provided by the microturbine TEG. This allows for the reuse of the windbox, combustion air blower, existing external FGR fan, existing distillate oil piping, and partial FGR ductwork. Therefore, the major hardware replacement focused on the retrofit of a new QLN burner and ancillary modification to the windbox to adapt the integration of the microturbine.

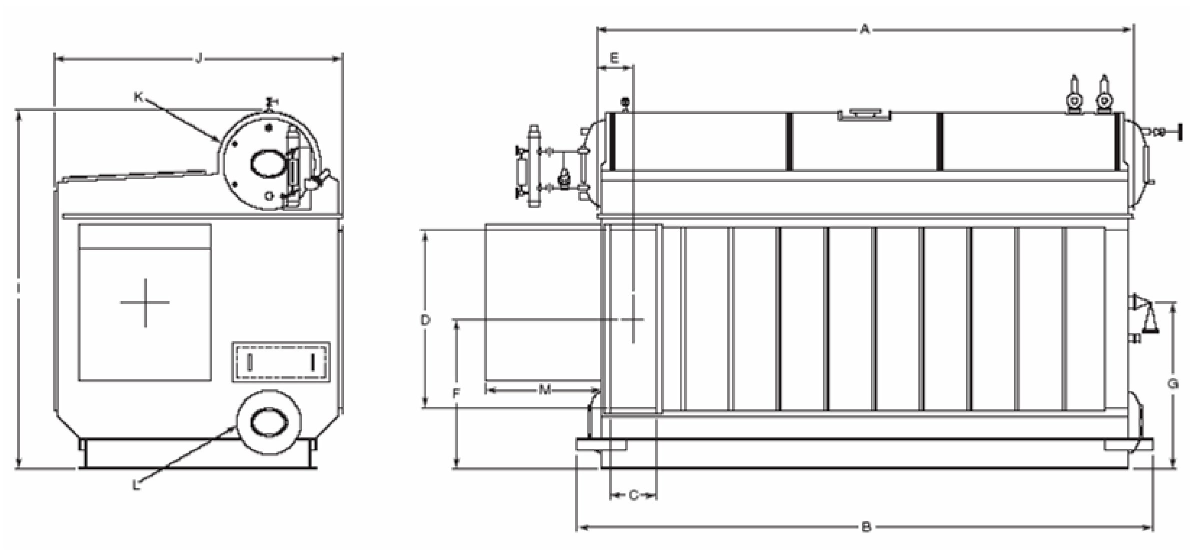


Figure 34: Conventional Watertube Boiler Configuration

Figure 35: Front View of Boiler No. 3 at Hitachi GST, San Jose, CA

Figure 36: Side View of Boiler Windbox- Pre-Retrofit

Figure 37: Side View of Boiler Windbox and Air Blower Pre-Retrofit

As part of the selection process and negotiations with Hitachi, the project calculated the estimated energy and cost savings associated with the self-generation of electricity with the proposed CHP. Figure 38 illustrates the estimated savings calculated for the Hitachi Steam Plant with the operation of the 80 kWe CHP system. Estimates depend on the differential cost of natural gas and electricity, as the use of the microturbine will increase the use of natural gas slightly. The simple cycle microturbine uses more fuel per kW generated. However, the impact on overall CHP natural gas use is the same as a recuperated microturbine because more of the waste heat is made available to the boiler with a simple cycle unit. As the Figure shows, savings amount to about $45,000/yr for a natural gas cost of $10/MMBtu and electricity cost of $12/kWh. These savings can be used to calculate the return on investment (ROI) for this site and other commercial sites. An ROI calculation for a similar installation based on 100 kWe CPS simple cycle microturbine is given in Section 7.

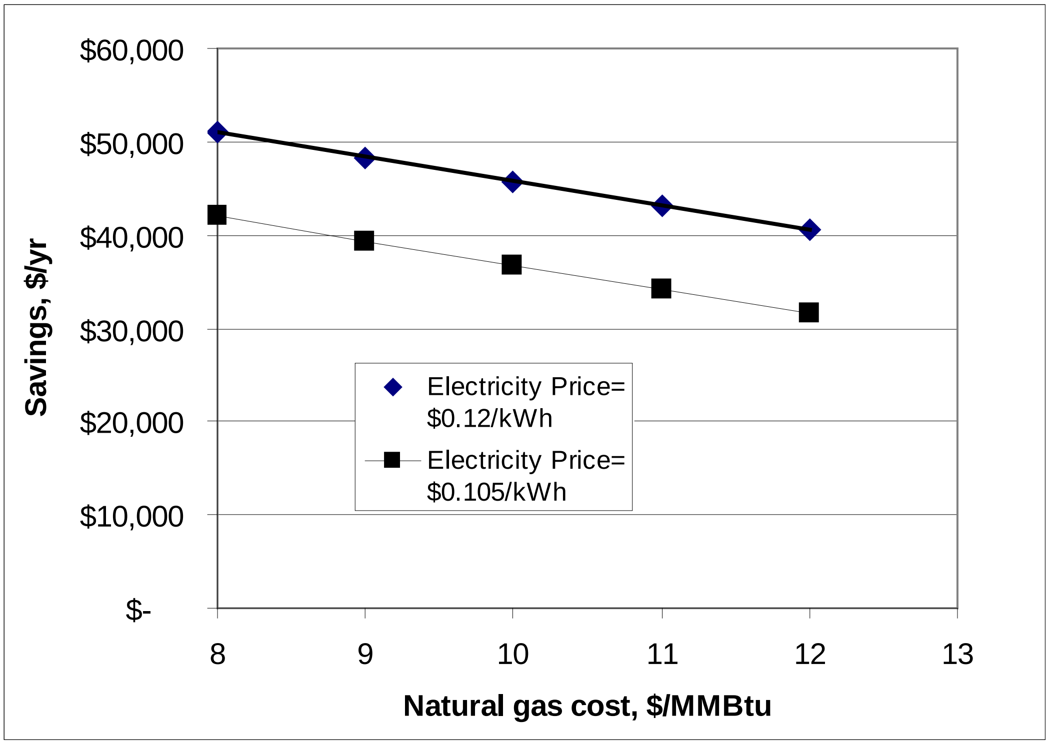


Figure 38: Estimated Host Site Savings with 80 kWe CHP

3.4.3 Field Installation

Figures 39, 40, and 41 illustrate the complete installation of the CHP system. Figure 39 shows the Coen QLN™ burner inside the windbox. The bustle for distributing microturbine exhaust in the burner premixed air slots is visible toward the front of the burner. Figure 40 illustrates the microturbine cabinet bolted to the side of the windbox. The hot section of the microturbine which includes the silo combustor and power turbine is located within the windbox to provide cooling. The cabinet incorporates a relay for the operation of the pilot gas. The relay controls the solenoid valve to the pilot to automatically shutoff the pilot fuel once the microturbine exhaust gas temperature (EGT) reaches a level equivalent to about 70 kW. At this firing rate, the silo combustor operates in fully premixed mode and the combustion is deemed stable for ultra-low NO_x operation. In its final installation, the bustle and power turbine are insulated with a thermal blanket to reduce heat losses. Any waste heat is removed by convection by the burner blower. The burner management system (BMS) for the QLN is in the foreground. The BMS controls the operation of the burner as well as the lightoff of the microturbine. The power electronics cabinet and gas compressor are located on the side of the boiler. Figure 41 shows the complete view of the boiler front with the new burner plate and

Figure 39: View of QLN Burner with Microturbine Bustle inside Windbox

3.4.4 Field Test Plan

The demonstration test has two principal objectives: (1) the validation of emission compliance with the BAAQMD rules and (2) the quantification of the energy gains and overall CHP efficiency. Table 6 shows that the test plan considered testing emissions and energy balance with and without the microturbine firing at set boiler firing rates. The plan considered the microturbine firing only at maximum generating capacity as this is the intended use. One other key operating condition for the boiler is the FGR level needed by the Coen ULN burner in order to meet the permitted NO_x limit of 15 ppm at 3 percent O_2. Three levels of FGR rate were considered to allow a determination of the NO_x performance of the Coen burner with different dilution levels and to establish the FGR rate, i.e., damper opening on FGR duct, at different boiler loads and with or without microturbine operation. Damper settings were then established for each condition in order to comply with air permit levels. As indicated in Table 6, the actual FGR rate is calculated with the measured combustion air dilution as determined by the oxygen concentration in the windbox. A separate FGR is contributed by the microturbine and must be added to the windbox FGR in order to calculate the total FGR to the ULN burner. For all test conditions considered when both the microturbine and ULN are firing, the overall NO_x and CO emission will need to be maintained below 15 and 50 ppm respectively in order to meet the BAAQMD permitted limits and also to demonstrate compliance with the ARB 2007 DG requirements of 0.07 lb/MWhr.

Figure 40: View of Completed Installation

Table 7 lists the measurements for each of the performance tests of Table 6. The plant's fuel gas flow meter was used to measure the gas flowrate to the CHP system, i.e., gas flow to the compressor inlet for the microturbine and to the low-NOx burner for the boiler. Feedwater and steam conditions, pressure and flowrate, measured in the boiler control room and steam gauges on the boiler itself, were used to establish the heat recovery in the boiler. Power generation from the microturbine was recorded by the power electronics cabinet. Boiler stack measurements were used to determine the emissions and thermal losses from the boiler. Emissions measurements with and without the microturbine on were used to quantify the incremental NOx emissions produced by the microturbine at various boiler loads. The oxygen concentration in the windbox was used to establish the additional ULN FGR, if any, that would be required to meet BAAQMD NO_x permit conditions. A detailed description of these calculations is given in Section 7.

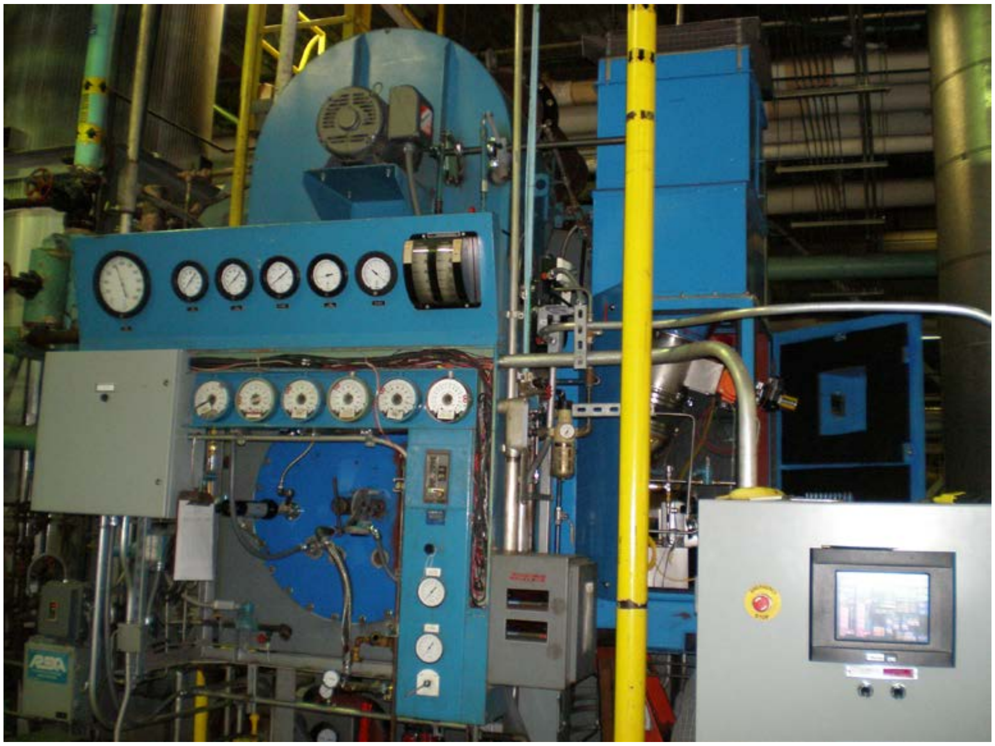


Figure 41: Boiler Front View with QLN™ Burner and Microturbine Installed

Table 6: Performance and Test Load Matrix

Run	MTG Load (kWe)	ULN Burner Load (MMBtu/hr)	External FGR (%)
1	Not Operating	10	As needed to meet permit NO_x level
2	Not Operating	15	
3	Not Operating	20	
4	Not Operating	25	
5	Not Operating	Max	
6	80	10	As needed to meet permit NO_x level
11	80	15	
12	80	20	
13	80	25	
14	80	Max	

These data was then used to quantify the efficiency of the boiler, microturbine and CHP system as well as compliance with permitted emission levels. Required measurements were performed for noise levels generated by the microturbine during CHP operation and were compared with noise levels from the boiler. Three sets of measurements were taken at each test condition at a frequency no less than ½ hr after operating conditions were stabilized. Steady state test conditions were based on the measurements not deviating more than levels identified in Section 7.

Table 7: List of Measurements and Data Sheet

Date				
Time				
Run #				
	Variable	**Units**	**Location**	**Value**
Ambient Conditions	Barometric Pressure	in of Hg	Ambient press gauge	
	W/B Air Inlet Temperature	^{o}F	Wet/Dry bulb gauge	
Gas Compressor	Inlet Gas Pressure	psig	Pressure gauge	
	Outlet Gas Pressure	psig	Pressure gauge	
	Power Consumption	kW		
	Gas HHV	BTU/ft^3	PG&E gas data	
	Gas LHV	BTU/ft^3	PG&E gas data	
Boiler and Burner	Steam flow	lb/hr	Boiler control room	
	Steam pressure	psig	Boiler control room	
	Feedwater pressure	psig	Boiler control room	
	Fuel gas flowrate	scfm	Plant fuel pipe	
	Fuel pressure	psig	Plant fuel pipe	
MTG	Inlet Temperature	^{o}F	Air filter inlet	
	Power Output	kW	Power Electronics	
	Fuel Flow	scfm	Plant fuel line	
Wind Box	W/B FGR Inlet Temperature	^{o}F	Boiler stack	
	W/B Outlet Pressure	in of water	Boiler Controls	
	Oxygen Level	%	Gas monitor	
CHP Emissions	Exhaust Temperature	^{o}F	Boiler stack	
	Oxygen Level	%	Boiler stack	
	NO_x Level	ppm	Boiler stack	

	CO Level	ppm	Boiler stack	

3.4.5 Field Test Results

A series of tests were performed during the first two weeks of October 2008 to establish emissions and overall efficiency performance of the boiler and microturbine working separately and in a CHP configuration. As indicated earlier, the designed system is not configured to allow the microturbine to be operational when the boiler is not firing. This is to prevent excessive CO emissions emitted from the microturbine. When the boiler is firing, CO emissions are readily oxidized to CO_2 in the boiler burner flame such that in a CHP mode CO emissions are maintained very low.

Section 7 lists the field data taken during these tests and specific test conditions. A total of 15 tests were performed. Tests focused primarily on monitoring emissions and performance with the boiler only and with both the microturbine and boiler firing (CHP mode). The microturbine silo combustor was operated with the pilot in the off position to permit very low NO_x emissions entering the boiler. Two additional tests were performed. The first test was performed with only the microturbine firing. This non-permissive condition was tested in order to monitor NO_x emissions contributed by the microturbine to the overall stack levels. A second test was performed in the permissive CHP mode with the silo combustor pilot in the on to monitor the impact on overall NO_x emissions and compliance. As anticipated, this second test indicated that NO_x emissions would exceed the permitted limits and therefore the pilot flame in the silo combustor must remain in the off position. Combustion in the microturbine remained stable with the pilot in the off position, indicative of acceptable performance with very low NO_x levels from the microturbine.

Emissions

Table 8 summarizes NO_x and CO levels measured with the boiler only firing and with boiler and microturbine in CHP configuration. Emission data indicates that both NO_x and CO were maintained well below the Air District permitted levels of 15 and 50 ppm respectively. NO_x levels were achieved with no external FGR (flue gas recirculated from the boiler stack to the QLN™ burner, reducing the energy consumption. When the microturbine was firing, the QLN™ burner was operating under a 5 to 10 percent equivalent FGR because the air supplied by the microturbine contains about 15 percent O_2. In addition, combustion air supplied by the microturbine reduces the air needed by the burner, thus reducing the load on the QLN™ combustion air blower.

Table 8: Summary of Emissions

Equipment	QLN Heat Input MMBtu/hr	MTG kW	NO_x, dry ppm@3% O_2	CO, dry @3% O_2
Boiler Only	13.8	0	10.5	22
	18.0	0	12.3	11
	26.8	0	12.4	8.0
	28.9	0	13.6	9.0
CHP Boiler and MTG(1)	11.9	76.2	11.8	4.9
	14.3	76.2	10.6	5.4
	16.5	80	11.2	3.9
	19.8	80	13.5	3.9
	21.8	80	12.0	3.8
	23.0	80	14.5	3.1
	24.0	80	13.3	3.1
	14.6	80	13.5	3.2
	26.5	80	13.7	2.1

1. Microturbine silo combustor pilot in off position.

Figures 42 and 43 illustrate the NO_x and CO profiles with boiler only and in CHP mode. The microturbine was found to generally add about 0.5 to 2 ppm NO_x to the boiler emissions, whereas CO emissions with the microturbine firing were actually reduced in spite of 650 ppm CO emitted by the microturbine. These results are attributed in part to the high EGT of the microturbine which provided higher flame temperature in the QLN™ premix zone.

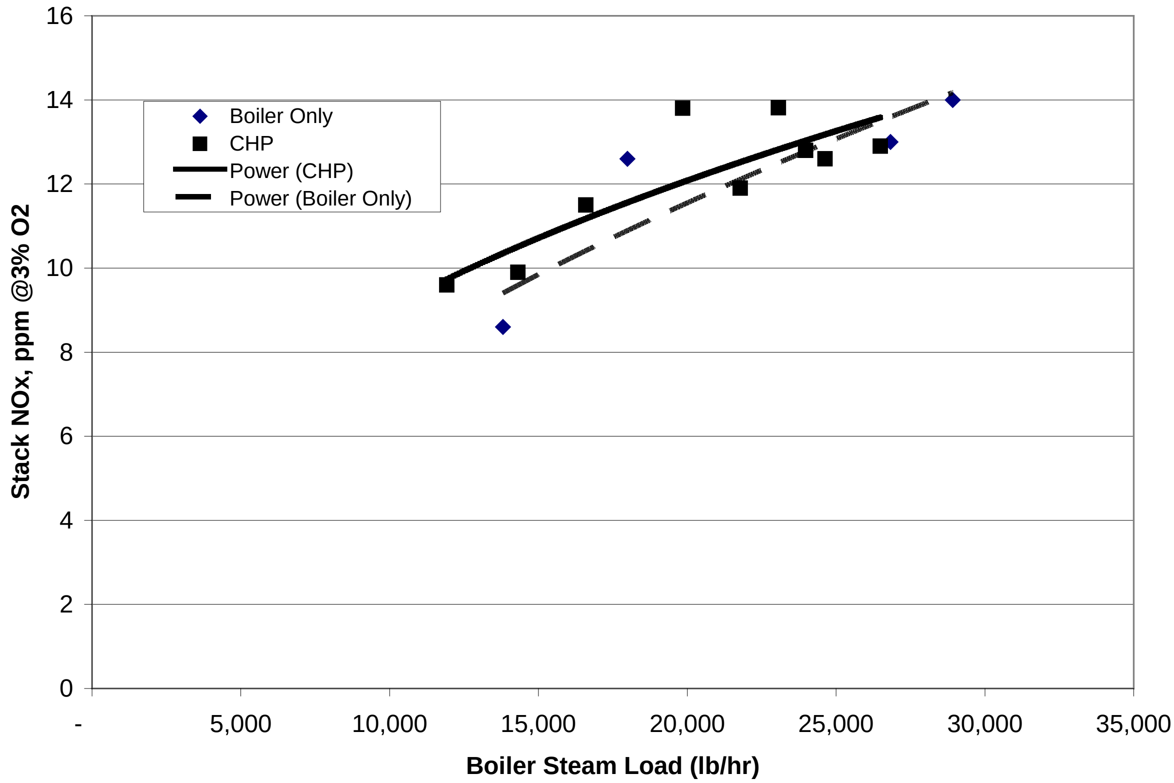


Figure 42: CHP NO_x emissions

Efficiency

Table 9 summarizes the results of efficiency calculations for both the boiler and combined microturbine-boiler operation when operating in the CHP configuration. The boiler efficiency was calculated using ASME PTC 4.1 heat loss method and was found to be slightly less than 80 percent. The power conversion efficiency is calculated by the fuel used in the microturbine and the kW generated. The low power conversion efficiency levels are consistent with the performance of simple cycle microturbines. The efficiency of the CHP averaged about 82.7 percent. The 3 percentage point increase with CHP compared to the boiler is due to the added energy recovered for power generation. The overall CHP efficiency is slightly higher at lower boiler loads because of the energy extracted for power generation makes up a higher percentage of the overall energy recovered. Figure 44 illustrates the effect of boiler stack excess O_2 on overall CHP efficiency. Because the boiler efficiency itself is reduced when excess combustion air increases, the overall CHP efficiency also shows a slight reduction. Higher combustion excess air levels necessary at lower boiler loads result in an increase in the dry gas heat loss.

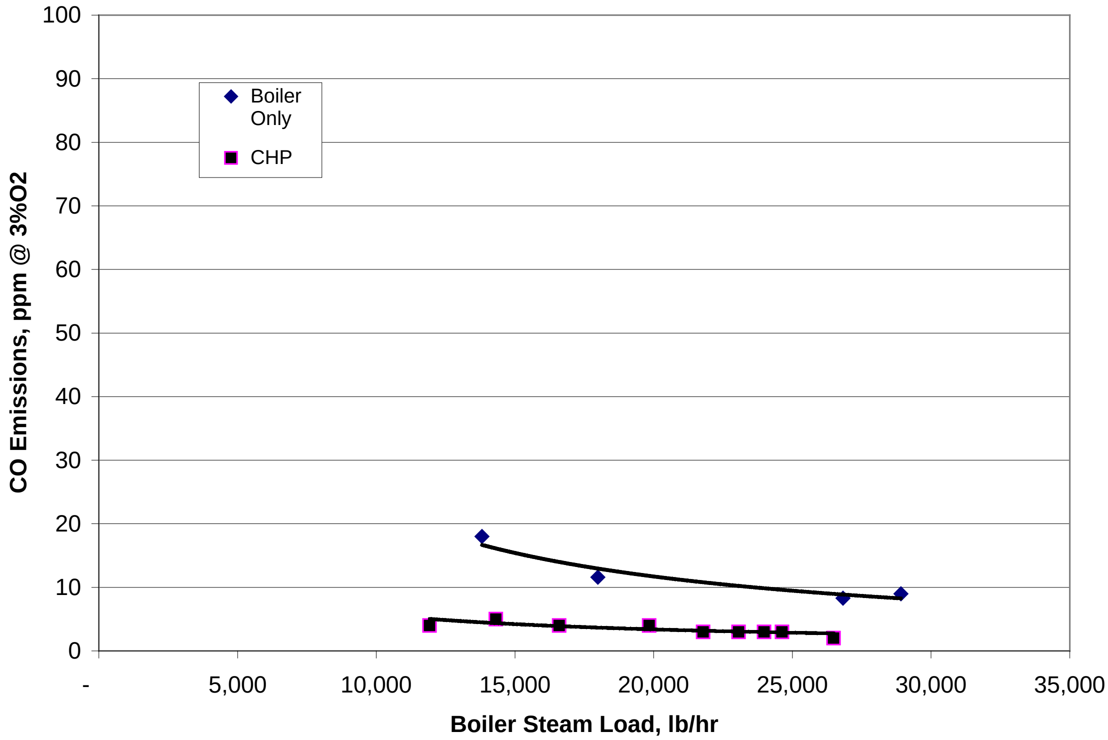


Figure 43: CHP CO Emissions

Table 9: CHP Efficiency at 80 kW MTG Output

Boiler Steam Load, x1000 lb/hr	Boiler	MTG Power Conversion	Overall CHP Efficiency
11.9	79.6	14.5	82.5
14.3	80.5	14.5	83.3
16.6	80.9	14.5	83.6
19.8	80.4	14.5	83.3
21.8	80.1	14.5	83.0
23.0	79.2	14.5	82.2
24.0	79.2	14.5	82.2
24.6	78.8	14.5	81.9
26.5	78.8	14.5	81.9
Average	79.7	14.5	82.7

Overall Performance

Table 10 summarizes the measured performance of the demonstrated CHP technology against the performance goals set for this project. Emissions for NO_x and CO are converted to lb/MWhr based on the simple cycle power conversion with combined recovery of the microturbine waste heat in the boiler according to ARB 2007 method attributing 3,412 kW for each MMBtu/hr of recovered microturbine waste heat. NO^x emissions are based on 3 ppm @15 O_2 measured from the microturbine, whereas CO emissions are based on boiler stack CO levels measured in CHP configuration. As indicated, both NO_x and CO levels are well below those necessary to meet ARB 2007 limits. The CHP efficiency target of greater than 80 percent set for this project was also achieved. Finally, this CHP technology will result in a lower carbon footprint for power generation. This project estimates CO_2 reductions of 0.26 tons/MWhr compared to gas-fired power generation at a modern central plant.

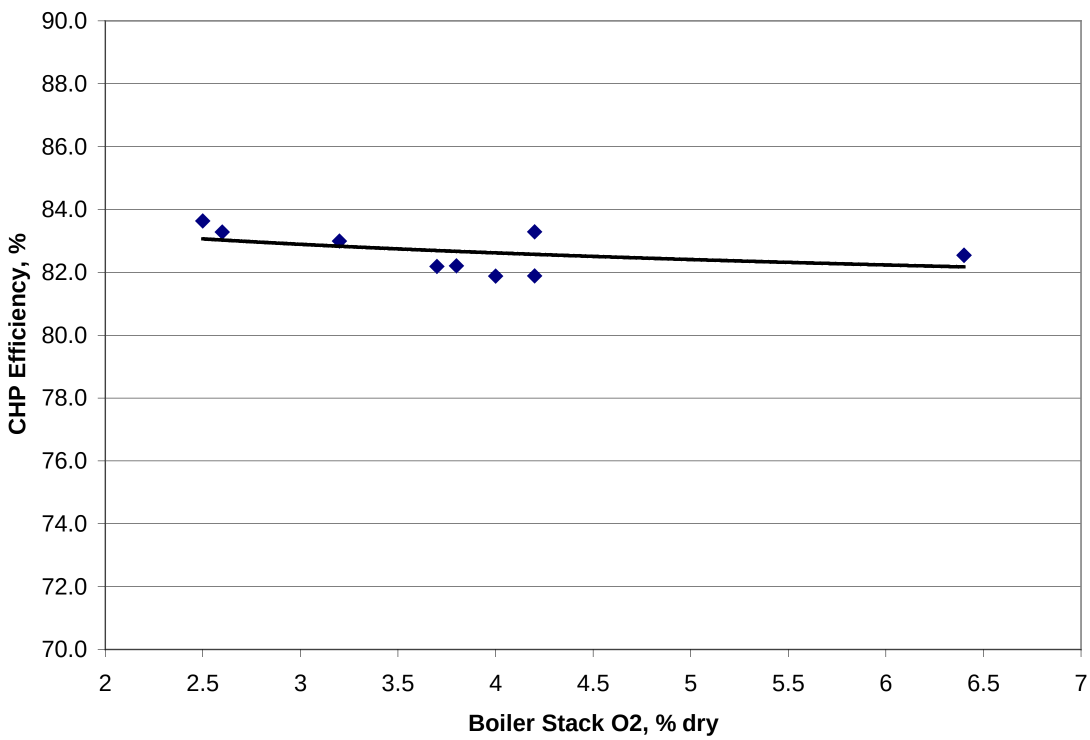


Figure 44: CHP efficiency with Boiler Stack O_2

Table 10: Overall CHP Performance

Performance	Integrated CHP	Project Goal
NOx, lb/MWhr	0.045	<0.07
CO, lb/MWhr	0.045	<0.10
CHP Efficiency, %	82.7	>80%
Reduction in CO_2 ton/MWhr	0.26	NA

3.5 Other Project Support Tasks

This section presents the results of Task 19, Technology Transfer Activities and Task 20, Commercialization Readiness Plan

3.5.1 Technology Transfer Activities

The objective of Task 19 was to attend conferences, symposia, and meetings to describe the progress of the technology development and to highlight the accomplishments and potential applications and benefits of this integrated CHP technology in targeted industrial/commercial markets.

The project team participated in several technology transfer activities during the course of the project. The following is a list of technical papers and poster presentations that were prepared and published in technical journals, and proceedings:

1. Castaldini, C. and A Bining, "A Novel CHP – Microturbine Integrated with Industrial/Commercial Boilers to Mitigate Climate Change Impacts," Poster Presentation Fifth Annual California Climate Change Conference, Sacramento, CA, September 8-10, 2008;
2. Castaldini, C. and A. Bining, "Novel Microturbine CHP Installation on an Industrial Boiler," Viewgraph Presntation to the California Alliance for Distributed Energy Resources, San Diego, CA, February 1, 2008;
3. Castaldini, C. and A. Bining, "Integrated Microturbine-Industrial Steam Boiler as a Clean and Efficient CHP System, Poster Presentation Fourth California Climate Change Conference, Sacramento, CA September 10-13, 2007;
4. Castaldini C. and A. Bining., "Power Generation Integrated in Burners for Packaged Industrial/Commercial Boilers." Second International DER Conference, Napa, CA, December 9, 2006;
5. Castaldini, C. and A. Bining., "Power Generation Integrated in Burners for Packaged Industrial/Commercial Boilers," <u>International Journal of Distributed Energy Resources, Vol 3, No. 4., ps.310-312,</u> November 2006;

6. CMC-Engineering, "Integration of Microturbine-Boiler", Poster Presentation 6th Annual Microturbine Application Workshop, San Francisco, CA, January 17-19, 2006;
7. C. Castaldini, "Power Generation Integrated in Packaged Industrial/Commercial Boilers," 6th Annual International Symposium on Distributed Energy Resources, Santa Clara, CA, September 7-9, 2005;
8. Castaldini, C, S. Londerville, and H. Mak., "Power Generation Integrated in Burners for Packaged Industrial/Commercial Boilers," GTI 2005, Orland, FL, February 1-2, 2005.

Appendix A in Section 6 provides copies of the technical papers prepared under this project

3.5.2 Production Readiness Plan

The goal of the plan is to determine the steps that will lead to the manufacturing of the technology developed in this project or to the commercialization of the project's results. The successful commercialization of the development CHP technology will require the following critical processes, equipment, facilities, personnel and resources:

- Secure agreements with CPS on the sale and delivery of simple cycle microturbines with new housing required for installation of the low NO_x silo combustor;
- Secure CPS for sale and delivery of auxiliary microturbine equipment such as gas compressor and power electronics cabinet;
- Secure manufacturing commercial facilities for the fabrication of low NO_x silo combustors for 100 kWe standard CHP microturbine;
- Secure manufacturing facility to assist CMC-Engineering in the assembly of CPS-supplied microturbine and low NO_x silo combustor into a new enclosure adaptable to the windbox configurations of commercial ULN burners;
- Execute service agreements for the microturbine with experienced field technicians;
- Execute supply agreements with Coen and other burner vendors for the integration of the new microturbine cabinets provided by CMC-Engineering with commercial ULN burners for package industrial and commercial boilers in the size range of 10 to 100 MMBtu/hr firing capacities;
- Execute agreements with sales representatives for industrial equipment to include this CHP technology for retrofit of existing boilers and for new boiler installations;
- Establish a trademarked name for the technology and prepare commercial and technical brochures to make public the availability of this commercial CHP technology in technical journals.

CMC-Engineering has already reached agreements with Calnetix, the parent company of CPS, to supply all microturbine related components with the exception of the new low-NO_x silo combustor. The silo combustor would need to be modified to increase its firing capacity for the upgraded CPS 100 kWe microturbine. CPS has discontinued the TA-80 microturbine during the course of this project. CMC-Engineering has also initiated preliminary discussions with Coen for the sale and manufacture of integrated CHP systems and with field service support personnel necessary to commission the microturbine and provide routine maintenance.

An important component of the commercialization success of this technology is the anticipated costs to upgrade the CHP components to meet the 100 kWe generating capacity of the CPS microturbine and to manufacture, install, and service the technology in industrial and commercial plants. Industry profit margins dictate the sale price of technology to the potential markets.

Table 11 lists estimates of the various costs associated with the launching of the first commercial unit. The cost estimates include remaining development and manufacturing of first complete CHP systems: These estimates are based on retrofit of a 30 MMBtu/hr boiler and include the cost of CHP components provided by CMC-Engineering, CPS and the ULN burner vendor. The cost of the ULN burner will vary significantly among different burner vendors. Therefore a range in cost is presented. Additional development is considered for the upgrade of the silo combustor dimensions to increase its firing capacity for a 100 kWe microturbine, now standard commercial unit sold by CPS.

Table 11: Estimated Development and Manufacturing Costs for Commercial CHP Systems

Cost Category	Component	Estimated Cost
Remaining Development	Increased capacity silo combustor for simple cycle 100 kWe CPS microturbine	$50,000
Sale of Microturbine Components	CPS supplied equipment:	
	• 100 kWe microturbine with new housing	$60,000
	• Gas compressor and power electronics	$31,000
	• Minor components and spare parts	$9,000
Manufactured Components	CMC-Engineering supplied equipment • Low-NO_x silo combustor	$10,000
	• Microturbine enclosure and assembly and windbox interface	$32,000
	Burner vendor components	
	• Coen ULN	$200,000
	• ST Johnson ULN	$80,000

Cost Category	Component	Estimated Cost
Installation	Mechanical and electrical contractors	$40,000
Startup and Commissioning	Engineering and field service contractors	$24,000
Total cost of first commercial 100 kWe CHP installation		$336,000 - $456,000

CHAPTER 4: Conclusions and Recommendations

Packaged boilers in industrial and commercial steam generation applications are an ideal thermal sink for small microturbine generators in CHP configuration. This project demonstrated a new approach in CHP technology and configuration based on the close integration of a low-cost simple cycle microturbine with and industrial ULN burner. The development work that led to the final field demonstration included: (1) modifications to an CPS 80 kWe microturbine to reduce NO_x emissions with a novel premix silo combustor; (2) repackaging the simple cycle engine so that it can closely coupled with the ULN burner windbox assembly; and (3) modifying the ULN to integrate TEG in a strategic manner to improve burner performance and meet air permit levels.

4.1 Project Accomplishments

This novel CHP technology which integrates a simple cycle microturbine with a low-NO_x industrial burner was installed and demonstrated on a packaged 30 MMBtu/hr watertube boiler located at an industrial steam plant in California. The CHP assembly was tested in accordance with local air permit regulations and was found to meet emission limits and energy efficiency performance targets established for this project. This demonstration showed that small scale distributed power generation can be accomplished with a heat rate of 4,150 Btu/kWhr which is 35 percent lower than the most efficient central power stations. These improvements in heat rate translate to CO_2 reduction on the order of 0.17 to 0.26 tons/MWhr and reduced dependence on fossil fuels for power generation. Overall CHP efficiency exceeded 80 percent while NO_x emissions at the demonstration site were also lowered by 50 percent from pre-retrofit levels.

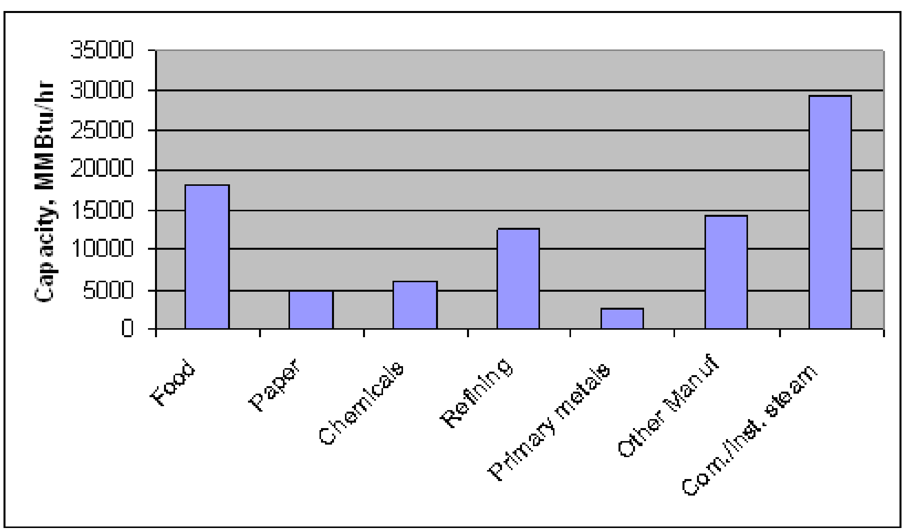
The demonstration of this CHP technology for retrofit to existing packaged boilers in California constitutes a significant advancement in promoting small100 kWe distributed power that is both environmentally sound and economically attractive to industrial users. Therefore, it is recommended that research agencies and air quality administrators in California continue to promote field demonstrations of this type to expand the portfolio of applications and include CHP as a technology to achieve energy efficiency goals along with improvements in quality gains.

4.2 Market and Commercialization Potential

As indicated earlier, the developed CHP technology targets industrial packaged boilers firetube and watertube alike as thermal sink for the waste heat from the simple cycle microturbine. These packaged burners operate with a single burner which must be capable of NO_x emissions as low as 9-15 ppm at 3 percent O_2 and must have significant load turndown capability. These burners are designed principally to deliver full firing capacity. Because of their fixed geometries, boiler efficiency can be significantly reduced at part load operation. This is an important effect on overall boiler efficiency because many boilers tend to operate well below full firing capacity. The application of the developed CHP technology can significantly improve operation both at full and part loads because of the added waste heat from the microturbine and increased ULN combustion stability at part loads.

The market for this CHP technology consists of both retrofit and new industrial package boilers in the size range from 5 to 100 MMBtu/hr heat input. The retrofit market avails itself of the ever increasing NOx emission standards imposed on these units which require replacement of older burners with newer ULN designs. Owners/operators will have the option of selecting ULN burners integrated with this CHP technology. This allows the facility to have a ROI on their capital investment while improving the operation of the facility. The market extends also to new boiler installations both in California and throughout the U.S.

A report prepared for GRI (now GTI)[3] in 1996 was used to determine the population of industrial boilers eligible for retrofit of this CHP technology (Reference 1). Based on the GRI inventory and projecting to 2008 using 2.5 percent growth per year, the total nationwide population of boilers in the 10-100 MMBtu/hr range is estimated at 33,000 units. Figure 45 illustrates the total capacity of industrial and commercial packaged boilers each with a firing capacity of 10 to10 MMBtu/hr located in California. These units are deployed in several industries as well as in commercial and institutional service such as district heating. The corresponding total number of boilers is illustrated in Figure 46.The 1,300 boilers in California represent nearly 1/25th of U.S population. Many of these boilers are located in Air Districts with strict environmental regulations and are required to reduce NOx emission due to industry growth, equipment upgrades designed to extend the useful operating life, or air quality attainment goals.



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[3] *Analysis of the Industrial Boiler Population*, Energy and Environmental Research, Report No. GRI-96/0200, June 1996

Figure 45: Estimate of Total Firing Capacity of Packaged Boilers in California, each with a Design Firing Rate less than 100 MMBtu/hr

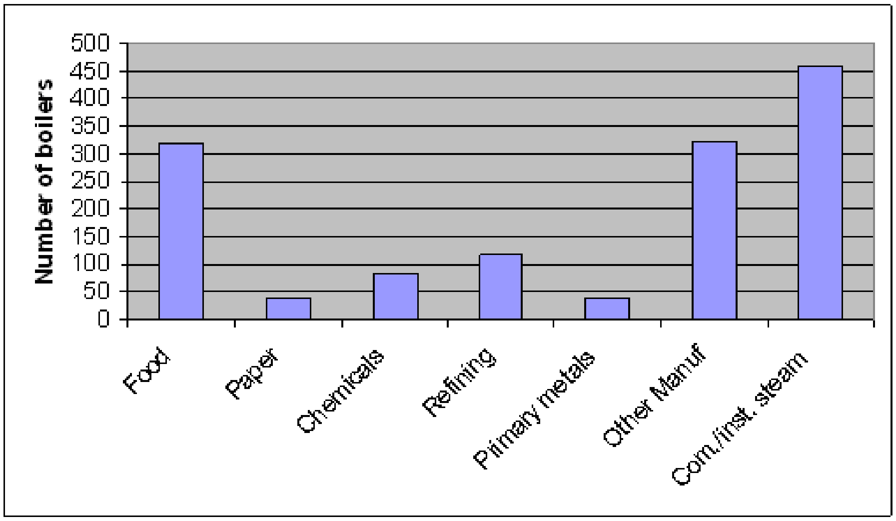

Figure 46: Estimated Number of Packaged Industrial Boilers in California, each with Firing Capacity of 10-100 MMBtu/hr

Because of the of the design efforts employed to maximize overall efficiency, this CHP technology would need only 4,170 Btu/kWhr additional heat input relative to a standalone industrial boiler. When compared to heat rates of either conventional or modern combined cycle central power stations, this can result in savings of 2,800 to 4,300 Btu/kWhr and equivalent CO_2 reductions of 0.26 tons/MWhr. Based on the available retrofit boiler population in California, this novel CHP technology has the potential to displace 138 MW of power generation with a 38 percent improvement in heat rate and reduce CO_2 emissions by 320,000 tons per year; with a significant contribution toward mitigating the California contribution to climate change .

4.3 Recommendations

Industrial packaged boilers offer an ideal thermal sink for small microturbine generators in distributed power CHP applications. The benefits of this technology extend beyond those of conventional CHP in that boiler operation, efficiency, and emissions are also improved. Industry can avail itself of the energy savings and economic paybacks with CHP when faced with requirements to upgrade existing burner technologies to comply with new and more stringent emission limits. This approach will ensure continued cost-effective industrial and manufacturing growth in the State without the environmental consequences of increased air pollution and climate change.

Therefore, the project team recommends that energy and air quality administrators in California promote the deployment of this CHP technology by providing incentives to cogenerate rather than simply force more costly controls to reduce NOx emissions. This will ensure that many potential industrial and commercial boiler sites include the CHP option in their decision making. The economic benefits of this CHP approach will outweigh many of the obstacles that have thus far prevented the rapid adoption of small-scale CHP and clean distributed generation.

GLOSSARY

Acronym	Definition
ABMA	American Boiler Manufacturer Association, Vienna, Virginia
ARB	California Air Resources Board
ASME	American Society of Mechanical Engineers
BAAQMD	Bay Area Air Quality Management District
BMS	Burner Management System - controls that monitor and control the operation of industrial burners
CEC	Combustion Control System part of Burner Management System (BMS)
CEC	California Energy Commission, Sacramento, California
CFD	Computational Fluid Dynamics - a computer based techniques for analyses of physical and chemical processes during combustion
CHP	Combined Heat and Power - the cogeneration of electricity and process heat using the thermal energy in the prime mover exhaust
CMCE	CMCE, Inc (d.b.a CMC-Engineering) - an engineering company dedicated to innovative engineering solutions in energy efficiency, alternative fuels, and air pollution control
CPS	Calnetix Power Solutions, Inc., formerly Elliott Microturbies, a wholly owned company of Calnetix
dB	Decibel, a logarithmic unit of measurement
DG	Distributed Generation - the generation of power close to the point of use
EESI	Elliott Energy Systems, Inc - manufacturer of packaged microturbine-based generators and CHP systems in Stuart, Florida, now renamed Calnetix Power Sulutions (CPS), a wholly owned company of Calnetix
EGT	Exhaust Gas Temperature (microturbine)
F	Fahrenheit
FD	Forced Draft - A term used to describe blowers that push air through the system rather than pulling it
FGR	Flue Gas Recirculation - the amount of flue gas recirculated back to the burner for NOx control

Acronym	Definition
FTA	Field Test Agreement - Written agreement with host site to demonstrate the technology
GHG	Greenhouse Gas
GRI	Gas Research Institute - the predecessor to the Gas Technologies Institute (GTI)
GST	Global Storage Technologies (a division of Hitachi, San Jose, CA)
HGST	Hitachi Global Storage Technologies, San Jose, CA
hp	Horsepower
ISO	International Organization for Standardization. Performance standards for gas turbines are based on 15° C and 1 atm ambient conditions
iwg	Inches water guage (pressure)
kWe	Electrical kilowatt (3,412 kWe per MMBtu for 100% conversion efficiency)
LBNL	Lawrence Berkeley National Laboratory - A Department of Energy Laboratory engaged in the study of scientific processes and technology development
LCAP	Low combustion air pressure (signal and switch in the BMS)
LSB	Low Swirl Burner - alias LSN, a burner nozzle technology patented by LBNL
LSN	Low Swirl Nozzle - a burner nozzle patented by LBNL for application on gas turbines and industrial processes
MMBtu	Million British Thermal Units - One Btu = 1055 Joules
MTG	Microturbine Generator - gas turbines with generating capacities generally typically 250 kWe or less
MWhr	million watts (electrical) per hour
NOx	Nitric Oxides - Combined NO and NO2 in combustion gases
PE	Power Electronics - cabinet containing all electronics components for operation of the MTG
PIER	Public Interest Energy Research - program within CEC for the development of energy efficient technologies in California
ppm	Parts Per Million (for gas species = millions of moles of a specie per mole of gas)

Acronym	Definition
psi	Pounds per Square Inches - measure of pressure drop
psig	Incremental pressure above atmospheric pressure in Pounds per Square Inch
PTC	Power Test Codes (ASME codes for measuring and calculating energy flows and efficiencies)
QLN	Quantum Low NOxTM - trade mark name of Coen ULN burner capable of 9 ppm NOx for industrial boiler installations
RD&D	Research Development and Demonstration
ROI	Return on Investment
rpm	Revolutions Per Minute (Microturbine)
scfm	Standard Cubic Feet per Minute - measure of gas flow
SCG	Southern California Gas Company - a division of Sempra Utilities engaged in the demonstration of energy savings technologies
SoCal Gas	Southern California Gas Company
TEG	(Micro) Turbine Exhaust Gas
TPSI	Turbine purge fan started interlock (system that guarantees purge cycle for microturbine)
TIDO	Thermal Isolation Damper Open - a damper used to isolate the MTG and prevent backflow from the windbox
ULN	Ultra Low NOx - reference to modern industrial burners that meet today's stringent NOx emission regulations

Appendix A

(Published as a separate document)